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Final Report

EFFECTIVENESS AND SERVICE LIVES/ SURVIVAL CURVES OF VARIOUS PAVEMENT REHABILITATION TREATMENTS

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Effectiveness and Service Lives/Survival Curves of Various Pavement Rehabilitation Treatments

Introduction

Transportation agencies spend billions of dollars annually on pavement maintenance and rehabilitation to meet public, legislative, and agency expectations. The effectiveness of various pavement rehabilitation treatments in terms of their impact on the pavement service life is essential for cost effective planning and programming of pavement maintenance, preservation and rehabilitation projects. Pavement deterioration rates, truck traffic volumes, environment, geology, and other factors have significant effects on the expected life of the pavement treatment. Given the role that pavement rehabilitation treatments play in pavement management programs, understanding the survivability of these treatments has the potential to allow improved resource allocation and more effective use of State funds.

The present research extends the traditional pavement management framework by formulating methodologies that enable the evaluation of the effectiveness of pavement rehabilitation treatments with respect to treatment service lives and costs. The end product of this research is a quantitative tool that can be used at the project development phase to estimate the effects of different types of pavement rehabilitation treatments for various road functional classes.

The first objective of the study is to forecast the pavement rehabilitation performance in time. In practice, pavement condition is characterized by a number of potentially interrelated performance indicators. Hence, it is of great importance to forecast the pavement's performance (in terms of all the condition indicators that play an influential role in the determination of the pavement's condition) as a system of equations, by explicitly accounting for simultaneous relationships that may potentially exist among performance indicators such as the pavement surface condition rating, PCR, (historically used by the Indiana Department of Transportation, INDOT, up to the year 2007), international roughness index (IRI) and rut depth (RUT) measurements.

The second objective is to approximate the service life of pavement treatments using statistical models with a set of pavement performance thresholds. This translates into estimating the service life of each pavement rehabilitation treatment for each road functional class to study the elapsed time until the pavement crosses a predetermined threshold that is considered critical.

The data used for the pavement performance statistical modeling were collected from the INDOT pavement management databases and from INDIPAVE (a database consisting of data on pavement condition, weather, pavement structure, traffic, maintenance, and other information at over 10,000 one-mile pavement sections in the State of Indiana). For purposes of performance modeling, values of pavement performance, traffic loading, weather effects and rehabilitation expenditure were obtained from these databases. Weather information was also collected from the Indiana State Climate Office. The data include information on 12,250 road sections from 1999 to 2007. The data were screened for its consistency and accuracy.

Findings

The pavement analysis in this study considers various combinations of pavement rehabilitation treatments (two-course HMA overlay with or without surface milling, concrete pavement restoration, three-course HMA overlay with or without surface milling, three-course HMA overlay with crack and seat of PCC pavement and 3-R and 4-R overlay or replacement treatments). Six road functional classes (rural and urban of interstates, non-interstates of the NHS, and non-interstates non-NHS) are considered. This allows for estimation of the performance and service life of the pavement, corresponding to each treatment and road functional class. Main findings are summarized below:

- More than 95 percent of the data points of the RUT pavement performance indicator were below 0.5 inches indicating that this type of distress has become relatively rare on INDOT highways.
- Data points of the PCR were scattered in a very narrow range (between a PCR value of 70 and 100) compared to the scatter of the IRI and deflection. Consequently, distinct thresholds can be obtained from the wide scatter of the IRI and the deflection. This suggests that IRI and deflection are more reliable performance measures than PCR when programming pavement rehabilitation treatments.
- Two-course hot mix asphalt, HMA, overlay (with or without surface milling) treatments were found to have a forecasted average annual deterioration in IRI of roughly 6 in/mi.
- Three-course HMA overlay with or without surface milling treatments were found to have a forecasted annual average deterioration in IRI of about 5 in/mi. Three-course HMA overlay with crack and seat of PCC pavement treatments were found to have a forecasted average annual deterioration in IRI of roughly 4 in/mi. Pavement projects identified as 3-R and 4-R overlay or replacement treatments were found to have a forecasted average deterioration in IRI in the range of 4 to 5 in/mi. Concrete pavement restoration treatments were found to have a forecasted average annual deterioration in IRI of roughly 7 in/mi.
- Average service life of two-course HMA overlay (with or without surface milling) was found to be roughly 10 years; 12 years for concrete pavement restoration; 12 years for three-course HMA overlay (with or without surface milling); 15 years for three-course HMA overlay with crack and seat of PCC pavement; and 15 years for 3-R and 4-R overlay or replacement treatments. These numbers match closely with the estimated service lives in the current INDOT design manual.

Unit cost of pavement rehabilitation treatment was strongly correlated (with a high degree of statistical confidence) to the service life prediction and consequently was used in the performance prediction models.

Implementation

Study results do not warrant changes to the INDOT Design Manual. However, a Microsoft Excel program was created to assist in quantifying the costs per improvements in pavement condition performance measures. INDOT can employ the software in generating estimated costs that can be used to assess the effectiveness of various rehabilitation treatments. This in turn can be used to provide support for decisions that must weigh the costs with the available budgets so that the best decisions can be made.

Additional research is recommended to establish remaining service life models for pavement rehabilitation treatments that are based on the AASHTO mechanistic empirical pavement design guide (MEPDG) models. Given the dependent variable will be the remaining service life, the independent variables must be simple, measureable, readily available (i.e. not stresses and strains) and adaptable in the INDOT pavement management systems.

Summary of the Service Lives of Rehabilitation Treatments

	Service Life (Lower-/Mid-/Upper- Year Estimates)					
	2C HMA	C PVM R	3C HMA	3C HMA PCC	3-R & 4-R	3-R/4-R
Rural Interstates	11/12/12	12/13/14	11/12/13	11/11/13	11/11/12	11/12/14
Rural Non-Interstates of the NHS	8/9/10	10/10/12	9/9/11	8/8/10	13/14/14	12/12/14
Rural Non-Interstates Non-NHS	11/11/12	10/12/14	10/11/14	10/12/15	19/20/21	11/13/14
Urban Interstates	10/11/12	11/13/14	9/10/12	12/13/14	11/12/12	12/15/15
Urban Non-Interstates of the NHS	8/9/10	13/14/15	8/10/12	9/11/13	9/12/13	10/19/20
Urban Non-Interstates Non-NHS	8/9/10	9/10/11	10/11/11	11/11/12	14/14/16	11/13/16

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Variable	Abbreviation
Two-course HMA overlay with or without surface milling	2C HMA
Concrete pavement restoration	C PVM R
Three-course HMA overlay with or without surface milling	3C HMA
Three-course HMA overlay with crack and seat of PCC pavement	3C HMA PCC
3-R and 4-R overlay treatments	3-R & 4-R
3-R/4-R pavement replacement treatments	3-R/4-R

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16. Abstract

The pavement analysis in this study considers various combinations of pavement rehabilitation treatments (two-course HMA overlay with or without surface milling, concrete pavement restoration, three-course HMA overlay with or without surface milling, three-course HMA overlay with crack and seat of PCC pavement and 3-R and 4-R overlay or replacement treatments). Six road functional classes (rural and urban of interstates, non-interstates of the NHS, and non-interstates non-NHS) are considered. This allows for estimation of the performance and service life of the pavement, corresponding to each treatment and road functional class. Main findings;

- More than 95 percent of the data points of the RUT pavement performance indicator were below 0.5 inches indicating that this type of distress has become relatively rare on INDOT highways.
- Data points of the PCR were scattered in a very narrow range (between a PCR value of 70 and 100) compared to the scatter of the IRI and deflection. Consequently, distinct thresholds can be obtained from the wide scatter of the IRI and the deflection. This suggests that IRI and deflection are more reliable performance measures than PCR when programming pavement rehabilitation treatments.
- Two-course hot mix asphalt, HMA, overlay (with or without surface milling) treatments were found to have a forecasted average annual deterioration in IRI of roughly 6 in/mi.
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- Unit cost of pavement rehabilitation treatment was strongly correlated (with a high degree of statistical confidence) to the service life prediction and consequently was used in the performance prediction models.

17. Key Words

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ABSTRACT

Transportation agencies spend billions of dollars annually on pavement maintenance and rehabilitation to meet public, legislative, and agency expectations. However, the effectiveness of various pavement rehabilitation treatments in terms of their effect on the pavement service life is not well understood. This is further complicated by the effect that physical deterioration, load volumes, weather, geology, and other factors may have on the effectiveness of the treatment. Given the role that pavement rehabilitation treatments play in the pavement-management program, understanding the survivability of these treatments has the potential to provide improved resource allocation and more effective use of State funds. The present research extends the traditional pavement-management framework by formulating methodologies that enable transportation agencies to evaluate the effectiveness of their pavement rehabilitation treatments with respect to each treatment service life. The end product of this research is a quantitative tool that can be used at the project development phase to estimate the effects of different types of pavement rehabilitation treatments for various road functional classes.

The models developed in this study are estimated using data from the Indiana Department of Transportation. The pavement performance is forecasted and influential factors that affect performance deterioration are identified. A system of equations approach is introduced, to explicitly account for simultaneous relationships that potentially exist among pavement performance indicators. To approximate the service life of the pavement rehabilitation treatments a set of pavement-performance thresholds are utilized.

A major contribution of this work is the demonstration of a general approach that can be applied for comprehensive analysis of the effects of pavement treatments, while taking into account specific characteristics of the infrastructure system. The results set forth herein provide a better understanding of the interrelationships among pavement rehabilitation treatment, pavement condition, road functional class, pavement service life, traffic loads and trucks, weather and soil condition, and rehabilitation expenditure. Moreover, this study illustrates the steps necessary to evaluate the pavement-treatment effectiveness and demonstrates how analysis can be carried out and ultimately improved. Given the complexity of the problem and the limitations of available data, this study should be viewed as an incremental step toward enabling transportation agencies to make better decisions regarding a number of pavement rehabilitation treatments, allowing the selection of treatment options that will last the longest given funding limitations.

CHAPTER 1. INTRODUCTION

1.1. Background and Problem Statement

Transportation Agencies spend billions of dollars annually on managing a wide range of assets to meet public, legislative, and agency expectations. These assets vary from the physical transportation infrastructure, such as roadways, structures, and their associated features, to equipment, material stocks, data and information, and human resources. Asset management can be associated with nearly every aspect of transportation agencies' work, including design, planning, engineering, finance, and programming.

With regard to the problem of pavement treatments, the effectiveness of various treatments in terms of their effect on pavement life is not that well understood. The issue is complicated further by the effect that physical deterioration, load volumes, weather and soil conditions, location (space) and other factors may have on the effectiveness of the treatment. Given the important role that pavement treatments play, understanding the survivability of these treatments has the potential to provide improved resource allocation and more effective use of State funds.

Pavement maintenance and rehabilitation is one of the most critical and costly forms of infrastructure asset management. Preserving pavements in an appropriate manner, extends their service life, and most importantly improves motorists' safety and satisfaction and saves public tax dollars.

Keenan (2005) defines pavement preservation as a system where pavement treatment occurs at an optimum time with the goal of maximizing pavement service life.

Another term typically used for pavement preservation is preventive maintenance which seeks to treat pavements before distress has reached a level where the structural integrity of the pavement is compromised. The actions required to restore pavements to a level where preventive maintenance can be applied, is defined as corrective maintenance. Pavements left to deteriorate without timely maintenance treatments are more likely to require major rehabilitation and reconstruction. Typically, pavements perform well until a point in their service life where their performance rapidly deteriorates to failure. It has been shown that investing in pavement preservation before that deterioration point significantly reduces future rehabilitation and/or reconstruction costs (Keenan, 2005), providing highway agencies with feasible alternatives in addressing pavement needs where pavement condition is improved and service life extended. Therefore, preserving pavements while optimizing the efficiency of investments, can improve the highway system and road-user satisfaction.

Typically, pavement preservation is conducted before the pavement's structure fails. In some cases, however, the treatment may not be relevant to the pavement's condition and the pavement may be treated long before or even long after its condition requires it. Hence, forecasting pavement conditions is very important because it allows for a reliable estimation of the pavement service life from the implementation of a specific treatment. Good models for performance forecasting have always been challenging (Darter 1980), due to the need to predict the pavement's performance and condition so as to determine optimal times to perform preservation activities, and predict their impacts on pavement condition and remaining service life.

The serviceability-performance concept plays an important role in pavement management. The effectiveness of a preservation treatment (also referred to as deterioration reduction) is indicated as the increase in 'positive' service attributes (or reduction in 'negative' attributes) of the pavement system. In pavement maintenance and rehabilitation, such effectiveness typically indicates an improvement of the surface condition (e.g., pavement condition rating (PCR), rutting depth, pavement quality index

(PQI), surface deflection, present serviceability index (PSI), etc.) or a deterioration of the surface roughness (e.g., international roughness index (IRI), roughness number (RN), etc. (Anastasopoulos, 2009a).

Given the size of the pavement management budget and the importance of pavement preservation in the sustainability of transportation infrastructure, an improved understanding of the effectiveness of various preservation treatments could ultimately save millions of dollars by allowing for more efficient allocation of resources. The findings of the present research study will enable better decisions regarding a number of pavement rehabilitation treatments, allowing the selection of pavement treatment options that will last the longest given the initial pavement's conditions, weather and soil conditions, load volumes and others factors that may be found to significantly affect the survivability of the various pavement-treatment options.

1.2. Research Objectives

The main objective of this research is to identify a comprehensive methodological framework that can be used to evaluate the effectiveness of pavement treatments with respect to each treatment's service life. To this end, various pavement rehabilitation treatments are evaluated for their effectiveness with regard to pavement life for various road functional classes.

There are two specific objectives. The first one is to forecast the pavement performance over time. That is, to investigate how pavement condition deteriorates over time, and identify the influential factors that affect this deterioration. In practice, pavement condition is characterized by a number of performance indicators. Each indicator may have no relationship with the other indicators, or may be somehow simultaneously related to them. In all cases, however, there is a correlation between poor pavement condition and poor performance indicators. Hence, it is of great importance to forecast the pavement's performance (in terms of all the condition indicators that play an influential role in the determination of the pavement's condition) as a system of equations, by explicitly accounting for simultaneous relationships that may exist among them.

The second objective is to approximate the service life of pavement treatments using a pavement performance analysis and a set of pavement performance thresholds. This translates into estimating the service life of each pavement rehabilitation treatment for each road functional class to study the elapsed time until the pavement crosses a predetermined threshold that is considered critical.

1.3. Research Scope

The scope of the present study is defined to address the problem statement in a comprehensive manner, while maintaining a realistic approach based on data availability. Various aspects of the study scope are:

- Coverage: The methodological framework focuses on six pavement rehabilitation treatments in the State of Indiana; two-course hot-mix asphalt (HMA) overlay with or without surface milling, concrete pavement restoration, three-course HMA overlay with or without surface milling, three-course HMA overlay with crack and seat of Portland cement concrete (PCC) pavement, 3-R (resurfacing, restoration and rehabilitation) and 4-R (resurfacing, restoration, rehabilitation and reconstruction) overlay treatments, and 3-R/4-R pavement replacement treatments. The first two are functional treatments (which are related to the surface or profile characteristics and their interactions with vehicles), whereas the rest are structural (which are related to the pavement's ability to carry loads) (Labi and Sinha, 2003a). Because the effect of each treatment is expected to be different among roads that serve different purposes, and the criteria used to set the serviceability threshold(s) differ based on the functional class of the road, the analysis is conducted at a road functional-class level. As such, the analysis is performed separately for rural and urban interstates, non-interstates of the National Highway System (NHS), and non-interstates that do not belong to the NHS. As pavement condition indicators, the international roughness index (IRI), pavement condition rating (PCR), rut depth, and surface deflection (which can be used only for the structural treatments) are utilized.

- Analysis Period: A nine (9) year study period starting from 1999 to 2007, is selected. For the purpose of the study, only road sections with available historical rehabilitation data are considered in the analysis (road sections rehabilitated in 1999 or after). This decision is based on the need of establishing rational comparison criteria and the availability of pavement condition, rehabilitation cost, road section length, traffic loads, weather and soil information, etc. However, information for many other road sections is reviewed to gain insights relating to the status of various rehabilitation treatments used in the State of Indiana.

1.4. Organization

This report starts with a general description of the methodological framework, followed by a comprehensive literature review which seeks to understand methodological approaches and findings of past research efforts. The main research objective is to formulate a methodological framework that can be used to study the relationship between different pavement rehabilitation treatments, pavement attributes, as well as temporal and spatial attributes, for pavement rehabilitation treatment projects in Indiana. The analysis involves the determination of the pavement performance indicators and subsequent forecasting of pavement performance (by accounting for potential simultaneous relationships among the indicators). Also, using pavement performance thresholds from the literature, the analysis provides an approximation of the pavement treatment service life and determination of important influential factors that significantly affect it. The final step of this research study involves the documentation of the results and conclusions.

CHAPTER 2. LITERATURE REVIEW

2.1. Introduction

Pavement management has become increasingly complex over the years due to significant traffic/population growth and limited resources. In view of this, in 1998, the American Association of State Highway and Transportation Officials (AASHTO) recognized the importance of infrastructure management for transportation agencies, and adopted it as a priority strategic initiative.

Infrastructure management can be associated with nearly any planning, engineering, finance, programming, construction, maintenance, and information systems activity, conducted by a transportation agency. However, pavements present transportation agencies with their most challenging management problem. Transportation agencies spend a very large portion of their budgets on pavement preservation and they continually seek to enhance oversight mechanisms not only to ensure that these investments are yielding their worth but also to ascertain the impact of changing funding levels on pavement performance. Proper pavement management can save money for transportation agencies, and improve the safety and satisfaction of the motorists.

2.2. Concepts and Definitions

Pavement management can be defined as a systematic process of cost-effectively maintaining, upgrading and operating pavements (FHWA, 1999). The scope of pavement management can be summarized in the following three steps (Galehouse et al., 2003); consideration of various investment strategies, provision of a rational decision process, and overall condition of the pavement system improvement at a lower cost.

Preventive maintenance is a planned strategy of cost-effective treatments to an existing roadway system that preserves the system, and delays future deterioration. As a tool for pavement preservation, preventive maintenance is associated with the on-time application of the appropriate non-structural treatments to different pavement types.

Pavement preservation typically includes corrective and preventive maintenance and sometimes minor rehabilitation projects. However, it may also include all the activities undertaken to provide and maintain serviceable roadways. New or reconstructed pavements, and pavements requiring major rehabilitation or reconstruction, are usually excluded. With pavement preservation investments in the highway system, pavement life is extended, pavement performance is improved, cost effectiveness is enhanced, and end users needs are met. Figure 2.1 illustrates a depiction on the pavement preservation vs. rehabilitation concepts.

Reactive maintenance typically includes unscheduled activities that respond to situations that are beyond the agency's control (e.g., pothole patching, rut filling, etc.). Emergency maintenance includes activities under extreme conditions when life and property are at risk (e.g., rockslides, earth slides, washouts, rigid pavement blowups, etc.).

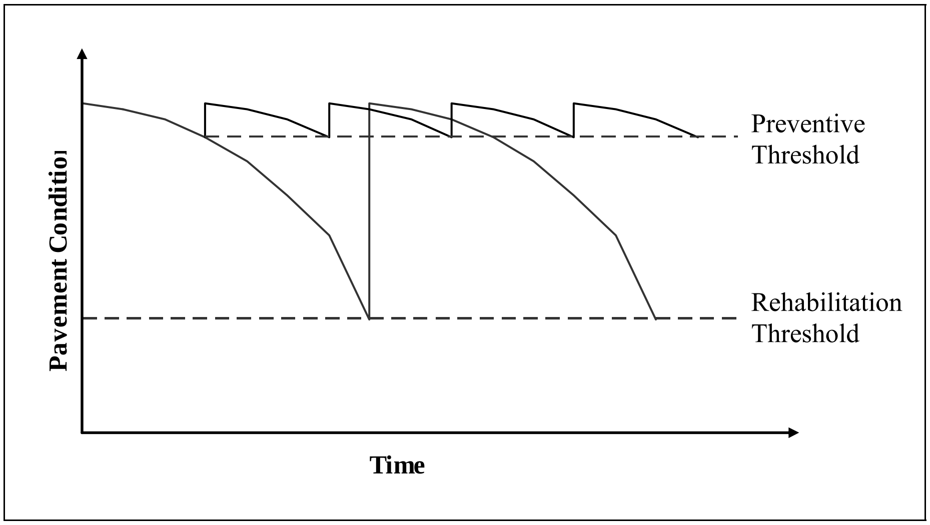

Figure 2.1 Pavement preservation practices

2.3. Types of Pavement Distress

There are different guidelines in determining the severity of pavement distress. Miller and Bellinger (2003) provide guidelines to identify the distress and the assessment of the level of severity. For flexible pavements, including asphalt overlays on asphalt or concrete pavements, distresses can be classified into:

- cracking (block cracking, edge cracking, fatigue cracking, wheel and non-wheel path longitudinal cracking, transverse cracking, and reflection cracking at joints),
- patching and potholes (patch, patch deterioration, and potholes),
- surface deformation (rutting and shoving),
- surface defects (bleeding, raveling, and polished aggregate), and
- miscellaneous distress (lane-to-shoulder drop-off, and water bleeding and pumping).

For jointed and reinforced Portland cement concrete (PCC) pavements, including concrete overlays on PCC pavements, distresses can be classified into:

- cracking (longitudinal cracking, transverse cracking, corner break, and durability cracking),

- joint deficiencies (transverse and longitudinal joint seal damage, and spalling of longitudinal joints and of transverse joints),
- surface defects (map cracking, scaling, pop-outs, and polished aggregate),
- patch/ patch deterioration (water bleeding and pumping), and
- miscellaneous distress (faulting of transverse joints and cracks, lane-to-shoulder drop-off and separation, and blowups).

For continuously reinforced concrete pavements (CRCP), distresses can be categorized into:

- cracking (transverse cracking, longitudinal cracking, and durability cracking),
- surface distress (pop-outs, scaling, map cracking, and polished aggregate), and
- miscellaneous distress (lane-to-shoulder drop-off and separation, spalling of longitudinal joints, water bleeding and pumping, longitudinal joint seal damage, blowups, transverse construction joint deterioration, patch/patch deterioration, punchouts).

In addition, the Indiana Department of Transportation (INDOT, 1998) developed the Pavement Condition Data Collection Manual where surface distresses are classified for flexible/composite pavements and jointed concrete pavements[1], as shown in Table 2.1.

On the other hand, the INDOT Design Manual (INDOT, 2008) provides another interpretation of distress classification:

- Flexible (asphalt) pavement: block cracking, rutting, shoulder drop-off, thermal cracking, alligator/fatigue cracking, weathering, stripping, flushing, frost heave, longitudinal cracking, polishing, raveling, and reflective cracking;
- Rigid (concrete) pavement: blow-ups, polishing, poor ride-ability, joint seal failure, alkali-silica reactivity, structural failure, pop-outs, corner breaks,

[1] Note that in this case, the surface deformations (i.e., rutting and shoving) and pavement roughness are evaluated separately from the pavement surface condition rating.

durability cracking, longitudinal cracking, punch-outs, transverse cracking, scaling, spalling, faulting, and joint failure.

Table 2.1 Composite/flexible and jointed concrete pavements distresses

	Composite/Flexible Pavement Distresses	**Jointed Concrete Pavements**
Distress Category	**Distress Type**	**Distress Type**
Cracking	Alligator Cracks Transverse Cracks Block Cracks Longitudinal Cracks Edge Cracks Widening Cracks	Corner Breaks Durability Cracks Transverse Cracks Longitudinal Cracks
Patching and Potholes	Patching Potholes	
Surface Defects	Raveling	
Surface Deformation	Rutting	
Joint Deficiencies		Transverse Joint Spalling Longitudinal Joint Spalling Transverse Joint Seal Damage
Miscellaneous	Pumping Maintenance actions	Pumping Faulting Maintenance

2.4. Pavement Treatments

To slow down pavement deterioration and reduce costs, preventive maintenance treatments in an early stage of the pavement's service life is crucial. According to Zimmerman and Peshkin (2004) typically applied preventive maintenance techniques include:

- For flexible (asphalt) pavement: microsurfacing, chip seals, fog seals, crack treatments, slurry seals, thin hot-mix overlays (less than 1.5 to 2 inches), mill and fill operations, maintenance of drainage features, and ultra thin friction course;
- For rigid (concrete) pavement: load transfer restriction, maintenance of drainage features, undersealing, diamond grinding and grooving, and crack and joint sealing.

Past research (Zaniewski et al., 1999; Mamlouk and Zaniewski, 1998; Geoffroy, 1996; Labi, 2001; Sharaf and Sinha, 1984) indicated the need to categorize maintenance terms and activities (e.g., preventive and corrective maintenance and activities). A distinction was also identified between major preventive maintenance (e.g., chip-sealing, thin overlay), which covers a section of pavement surface, and minor preventive maintenance (e.g., joint sealing, joint/bump repair) which is localized. Table 2.2 and Figure 2.2 present a proposed characterization of pavement maintenance.

Table 2.2 Typical treatments in various categories of pavement treatment activities (Source: Labi and Sinha, 2003a)

INTERVAL AND FUNDING ⇨			Routine Maintenance		Periodic Maintenance		Capital Investment
Function: ROLE LEVEL ⇩	COVERAGE ⇩	⇩	Force-Account	By Contract	Force-Account	By Contract	
Preventive Treatments	Only Affected Locations	Minor (localized)	Crack Sealing Bump Repair	N/A	N/A	Undersealing Stitching	N/A
	Entire Surface (typically)	Moderate (thin coat)	N/A	N/A	Chip Sealing Sand Sealing	Chip Sealing	N/A
		Major (thin overlay)	N/A	N/A	N/A	Micro-surfacing Thin Overlay	N/A
Corrective Treatments	Only Affected Locations		Patching (Shallow and Deep)	N/A	N/A	Patching (Shallow and Deep)	N/A
	Entire Surface		N/A	N/A	N/A	N/A	Resurfacing/ Restoration Reconstruction [1]

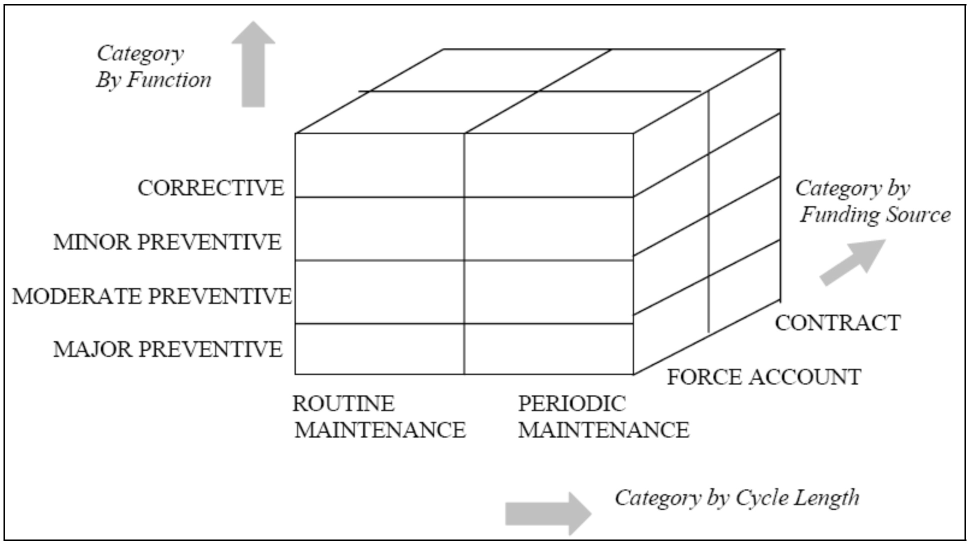

Figure 2.2 Pavement preservation practices (Source: Labi and Sinha, 2003a)

Figures 2.3 and 2.4 show typical corrective and preventive maintenance treatment practices in Indiana, respectively. The diagrams identify whether each corrective or preventive activity is typically carried out by contract (under the capital expenditure account) or in-house (under the force-account).

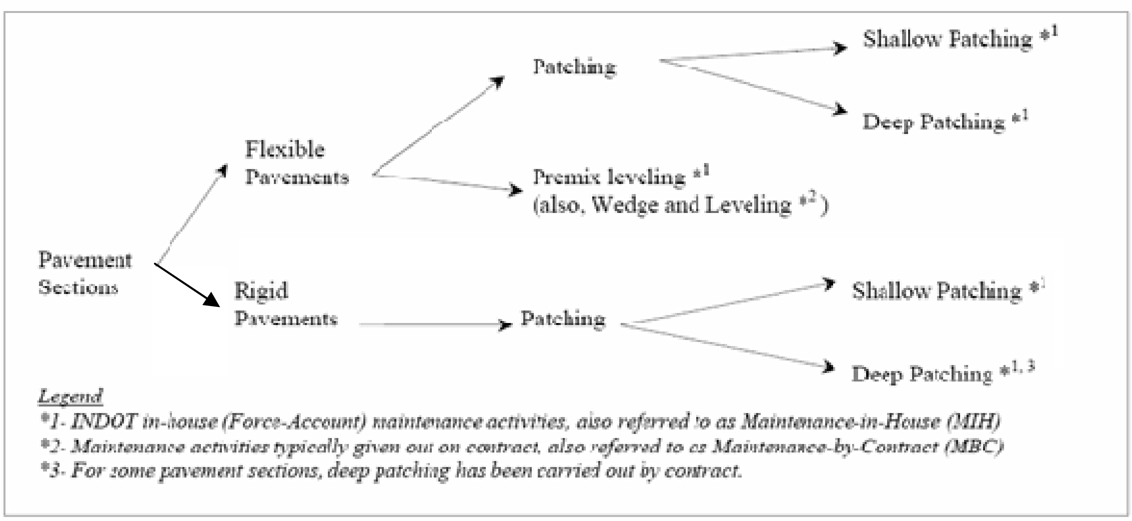

Figure 2.3 Typical corrective maintenance treatment types in Indiana
(Source: Labi and Sinha, 2003a)

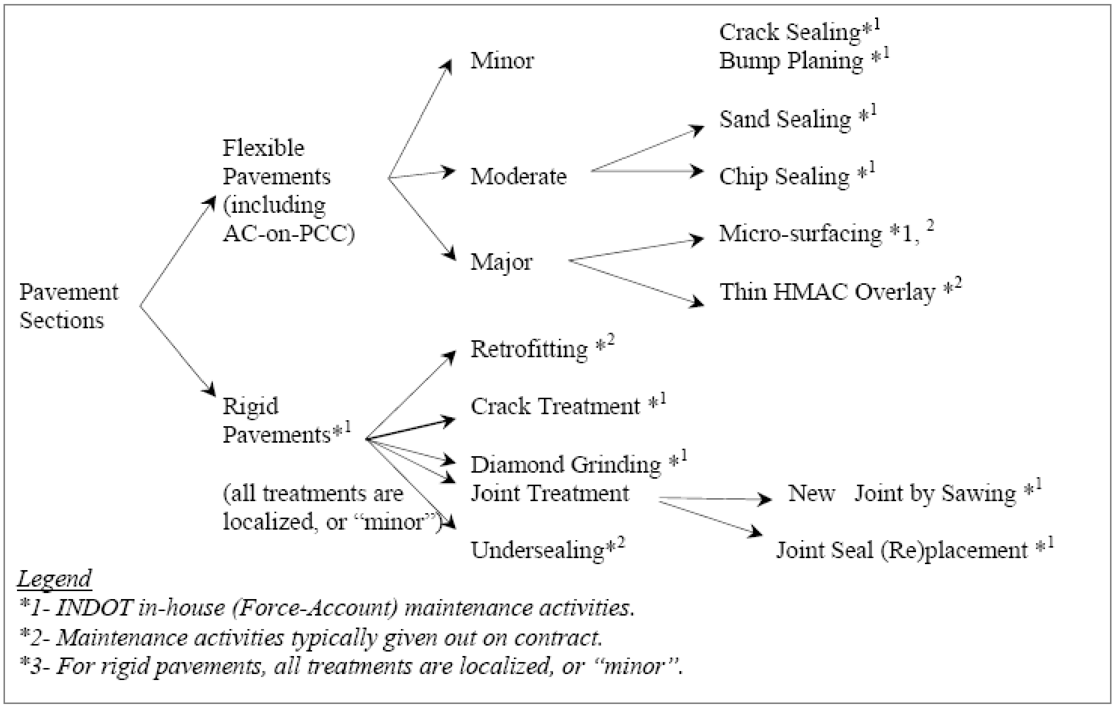

Figure 2.4 Typical preventive maintenance treatment types in Indiana
(Source: Labi and Sinha, 2003a)

2.4.1. Flexible Pavements

Water and moisture are important factors in the deterioration of pavements. Water typically enters the flexible pavement structure through cracks in the pavement surface and shoulders and through their longitudinal joints. The typical preventive maintenance treatments for flexible pavements are listed below.

- Crack sealing and filling: Both are preventive maintenance treatments for flexible pavements. According to the Strategic Highway Research Program (SHRP; Smith and Romine, 1993 and 1999), crack sealing is defined when specialized materials are placed into or above working cracks (using appropriate configurations to prevent debris and moisture intrusion into the cracks), whereas crack filling is defined when they are placed into non-working cracks (to essentially reinforce flexible pavement and reduce water infiltration) (Smith and Romine, 1993 and 1999; INDOT, 2008). Methods to seal and/or fill cracks include routing the crack to form a reservoir of sealer and using a polymer-modified polyester fiberized asphalt for the sealing material, or cleaning the debris out of the crack using compressed air and then spreading a hot asphalt sealer over the crack with a squeegee (Ponniah and Kennepohl, 1996; Chong and Phang, 1985).

- Chip sealing: It is defined as a bituminous/asphalt material and coarse aggregates full-width application to prevent surface deterioration and correct extensive cracking and surface failures (INDOT, 1998 and 2008). A layer of small crushed stone is spread on the pavement, after spraying it with an asphalt emulsion with a liquid asphalt distributor. Chip sealing is also used to increase the pavement's friction and can be used to correct pavements suffering from skid resistance loss, raveling, oxidation and surface permeability. However, chip-sealing is not recommended on high traffic-volume pavements due to hazards resulting from flying chips, relatively short life expectancy, roughness and excessive noise (Shuler, 1984). Chip sealing is suggested (INDOT, 2008) in road sections with low traffic-volume sections (annual average daily traffic (AADT) of less than 2,000 vehicles/day), surface age of 5 to 8 years, medium Pavement Condition Rating (80 to 90 PCR), alligator cracking, roughness (the pavement terminal/serviceability index (PSI)) greater than 3, and low rutting (less than 0.25 inches).

- Sand sealing: Similar to chip sealing, sand sealing is defined as a full-width continuous sealing of the surface with asphalt material and aggregate to prevent pavement deterioration (Mouaket et al., 1992). It is typically preferred on road sections with relatively few cracks, provides improvement of the surface by mitigating the effects of aging, waterproofing and low severity crack sealing. It is not recommended for application on existing sand surfaces. Sand sealing is considered to be more cost effective than chip sealing, but less effective in terms of performance (Mouaket et al., 1992).

- Thin hot-mix asphalt (HMA) inlays (milling and filling): According to INDOT (2008), it is defined as replacing the existing surface with a new asphalt surface to the original surface elevation, after milling it. It is suggested that the surface condition should not have significant potholes, depressed cracks, or major distresses, and that correct timing of implementation is crucial to the treatment's longevity. Thin HMA inlays are suggested in road sections with corrugations or wash-boarding in the surface course, surface age of 7 to 10 years, medium-low Pavement Condition Rating (75 to 85 PCR), roughness between 2.5 and 3.5 PSI, high rutting (greater than 0.5 inches), and for pavement surface friction improvement.

- Thin hot-mix asphalt (HMA) overlays: For high traffic-volume road sections where obtaining satisfactory performance is no longer possible, thin HMA overlay of l.75 inch or less is applied, and its service life typically is 8 to 11 years (Peterson, 1989). Thin HMA overlays are suggested in road sections with medium-low Pavement Condition Rating (75 to 85 PCR), extensive raveling of the surface, roughness less than 3 PSI, medium-low rutting (less than 0.5 inches), and for preventive maintenance on lower traffic-volume roads over existing successive chip seals to restore rideability (INDOT, 2008).

- Micro-surfacing: It is defined as a mixture of polymer-modified asphalt emulsion, crushed mineral aggregate, mineral filler, water and additive to control the time to harden. Micro-surfacing is typically used to fill ruts up to 2 inches in depth, to improve surface texture, and to seal surface cracks (Raza, 1994). Its success depends on the pavement condition and traffic loads (Raza, 1994; Hixon and Ooten, 1993).

The typical corrective maintenance treatments for flexible pavements are listed below. Note that corrective maintenance involves a reactive approach in pavement maintenance and typically is not considered as pavement preservation.

- Premix leveling: According to INDOT (2001), it is used to correct surface failures and depressions at bridge ends, and pipe replacements and deep patches caused by settlement, involving the use of minor machine or hand leveling and wedging of small isolated areas of concrete or bituminous shoulder and roadway surfaces with cold or hot bituminous mixtures. The area to be leveled is marked and cleaned, light bituminous tack coat is applied, the bituminous mixture is spread, the premix is hand ranked and the edges are feathered before rolling, and the mixture is compacted assuring that the existing surface and pavement edge, and the final layer are matched. Premix leveling of long road sections to account for minor crown deficiencies, or settlement between road and paved shoulder surfaces, or grade and rutting depressions, typically is considered for minor improvement projects.

- Shallow patching: It is used to correct potholes, edge failures, and other potential surface hazards by patching to a partial depth using cold or hot bituminous mixtures and hand tools (INDOT, 2001)[2]. Surface failures greater than 1 inch in diameter and 2 inches in depth are referred to as corrective maintenance, whereas other low-hazard-to-traffic surface failures are typically scheduled as preventive maintenance.

- Deep patching: It is used to correct extensive surface failure caused by blowup, settlement, or base failure, and includes the full depth removal of base and surface material and replacement with compacted bituminous mixture (INDOT, 2001).

[2] It also includes temporary patching of concrete and bituminous surfaces and the use of hot liquid bituminous material and aggregate for patching bituminous surfaces or crack and joint spalling of concrete surfaces.

2.4.2. Rigid Pavements

Rigid pavements' overall performance can be categorized as functional (which is related to the surface or profile characteristics and their interactions with vehicles), and structural (which is related to the pavement's ability to carry loads) as discussed in Labi and Sinha (2003a). Rigid pavement preventive maintenance activities typically are designed to address functional deficiencies such as reduced friction from wheel paths, inadequate cross-slope and poor drainage, roughness due to concrete durability, and rutted pavement surface due to pavement deterioration from tire chains used during snowfalls. The typical preventive maintenance treatments for rigid pavements are listed below.

- Joint and crack sealing: Similar to the flexible pavements, the cracks should be routed and sealed. Properly sealed joints and cracks can prevent infiltration of incompressibles into the joint and cracks, reduce moisture entering the pavement structure, and therefore increase the pavement's service life (FHWA, 1989). It is one of the most cost-effective preventive maintenance techniques and is considered as important as the sealing of transverse joints (McGhee, 1995). Its service life is between 2 and 8 years and depends on the preparation, and type and placement of the material used for the joint or crack opening. Longitudinal and contraction joints on concrete pavements should be inspected periodically and cleaned and resealed as required, as the timely sealing of the joints prevents problems generated by moisture and dirt[3] (INDOT, 2008).

- Undersealing: It is defined as filling any existing air-pockets under the concrete slab, by pumping cement, bitumen or other pozzolanic mixtures into the air-pocket (NRC, 1994). Water entering the pavement structure through joint faults results to rigid-pavement pumping, which in turn (under traffic loads) leads to water beneath the concrete slab through the cracks and joints.

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[3] Sealing and sawing of the joints should be considered in cases where 10% of the joints have loose, missing, or depressed sealant.

- Relief joint provision: It is defined as the provision of relief joints at certain intervals of the continuous concrete slab (especially at locations near the end of the bridge decks) to allow for the concrete slab expansion.

- Diamond grinding: It is defined as a restoration or improvement of pavement rideability by removing surface defects that develop based on traffic loading and environmental conditions (INDOT, 2008). It is used to correct low-severity faulting (when it exceeds 0.5 inches for 20% of the joints, and when the PSI is 3.5 or above) to slow down further development of the distress, and is considered feasible when joints are faulted 6 mm or less and if the pavement is not previously ground. Slab replacement or dowel provision is suggested in cases of sever faulting (Yu et al., 1994; Hall et al., 1993; McGhee 1995). Heavy traffic loads on roadways where deteriorated joints or other surface defects are encountered, results in accelerated dynamic loading of the pavement surface, increases deterioration, reduces serviceability, and increases user and maintenance costs. Diamond grinding enhances pavement friction as it modifies the surface in a way to provide ample channels for water to escape the surface resulting in reduced hydroplaning potential.

- Load transfer retrofit: It is used to restore the integrity of load transfer at the joints, and is typically applied together with diamond grinding to remove existing faults at joints and cracks (Ferragut and Papet, 1994).

- Underdrain maintenance: It is used to improve subsurface drainage[4] (that may cause premature pavement failure) for existing pavements or during construction of new pavements, and can considerably increase pavement service life (Forsyth et al., 1987; Christopher and McGuffey, 1997).

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[4] Drainage inspection and cleaning is performed on drainage structures such as underdrain outlets, ditches, catch basins, and inlets, to maintain or restore the flow of water (INDOT, 2001 and 2007). Other measures to improve subsurface drainage include joint and crack sealing, and construction of permeable base courses.

- Stitching: In jointed concrete pavements constructed without mechanical load transfer devices across the joints, significant faulting can occur as the result of poor load transfer when vehicles move across pavement slabs. In jointed concrete pavements constructed with dowels, the latter could become loose under heavy traffic loads. Such failures can lead to pumping and slab failure. To stitch such cracks, double-V-shear, miniature I-beam and figure-8 devices, and retrofitted dowel bars, can be used (Hall et al., 1993).

The typical corrective maintenance treatments for rigid pavements are listed below. Note again that corrective maintenance involves a reactive approach in pavement maintenance and typically is not considered as pavement preservation.

- Partial depth repair: It is used where concrete deterioration is confined to the top 1/3 of the concrete slab, to improve the pavement's rideability and reduce moisture and intrusion infiltration of incompressibles into the joints[5] (Jain, 2004).

- Full depth repair: It is used for pavement structural integrity restoration at spots where several structural deficiencies and distress types are observed (e.g., joint lock-up and slab break-up, faulting or spalling where over 1/3 of the pavement surface is affected, etc.), and involves sawing the pavement to its full depth, removing the distressed slab without damaging the adjacent slabs, removing and replacing the sub-base material (providing drainage if necessary), and placing the new concrete (Yu et al., 1994).

- Construction Joint Repair: It is used to repair a series of closely spaced transverse and interconnecting cracks near the construction joint (Jain, 2004).

- Punch-out Repair: It involves the repair of downward punching or loosening concrete blocks formed on the rigid pavements, caused when two closely spaced

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[5] The pavement is saw-cut to an appropriate depth, and the deteriorated concrete is removed and replaced.

cracks near the pavement edge and a short longitudinal crack between the transverse cracks are present (INDOT, 2001; Jain, 2004). The cracks widening and deepening, along with the steel reinforcement rupturing, over time create punch-outs.

2.4.3. Asphalt Concrete – on – Portland Cement Concrete Pavements Maintenance

Sawing and sealing is typically used when reflection cracking occurs on asphalt concrete on Portland cement concrete pavements (AC-on-PCC) (due to horizontal and vertical movements of the existing pavement structure joints and cracks[6]). It involves sawing a joint in the AC overlay above the existing joint and then sealing the latter, and it has been found to improve AC overlay rideability and reduce transverse reflection cracking for pavements with long service lives (Kilareski and Bionda, 1997). INDOT (2008) uses this method on HMA surfaces where reflective cracks or relatively straight single joints have developed. The treatment is typically performed within the first four years of the surface life, but may also be periodic as the pavement ages and more cracks develop.

2.5. Pavement Performance Modeling

2.5.1. Short Term Pavement Performance Modeling

The effectiveness of pavement maintenance or rehabilitation treatments can be indicated as the increase in ‘positive’ service attributes (or reduction in ‘negative’ attributes) of the pavement system. Maintenance or rehabilitation effectiveness, with respect to the number of monitoring periods used in its determination, can be measured by simply taking two points in time, just before and right after treatment, with the results

[6] This may be induced by daily seasonal temperature and traffic loads variations.

indicating an instantaneous performance jump. Other ways to measure maintenance or rehabilitation effectiveness are as follows:

- Use one measurement taken at a specified point in time before treatment, and another taken right after treatment;
- Use one measurement taken at a time before treatment, and another taken at a specified point in time right after treatment;
- Use one measurement taken at a specified point in time before treatment, a second measurement taken at a time just before or right after treatment, and a third measurement taken at a specified point in time well after treatment. This method enables the evaluation of maintenance or rehabilitation effectiveness for a time period (i.e., number of months, years, etc.) in terms of reductions in the deterioration rate.

Maintenance or rehabilitation treatments may adjust the pavement condition as follows (Lytton, 1987; Markow, 1991; Mamlouk and Zaniewski, 1998):

- The current pavement condition (measured after a finite time period or instantaneously) is modestly improved;
- The deterioration rate is reduced;
- The current pavement condition is modestly improved, and the deterioration rate is reduced.

According to Labi and Sinha (2003a, 2004) there are three measures of deterioration reduction: deterioration reduction level; performance jump; and deterioration rate reduction.

The deterioration reduction level (DRL)[7] is defined as the improvement of the pavement condition due to maintenance or rehabilitation, based on measurements of

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[7] In literature, DRL is also referred to as the delayed measurement of deterioration reduction, subsequent reduction in deterioration, or change in deterioration.

deterioration taken between two consecutive points in time (typically one year). Figure 2.5 illustrates a section of a performance curve. Note that point A is the pavement condition at a point in time before treatment, point D is the pavement condition just before treatment, point F is the pavement condition right after treatment, point E is the pavement condition at a point in time after treatment, and points W and Z indicate geometrical construction. Points C_i and t_i correspond to the pavement condition and monitoring measurement with respect to any point i, respectively. The DRL can be computed as follows:

- $\text{DRL}_{\text{Type I}}$ – Deterioration difference between a point in time (typically one year) before treatment (A) and right after treatment (F), illustrated as ΔC_1;
- $\text{DRL}_{\text{Type II}}$ – Deterioration difference just before treatment (D), and a point in time (typically one year) after treatment (E), illustrated as ΔC_2;
- $\text{DRL}_{\text{Type III}}$ – Deterioration difference at a point in time (typically one year) before treatment (A) and a point in time (typically one year) after treatment (E), illustrated as ΔC_3.

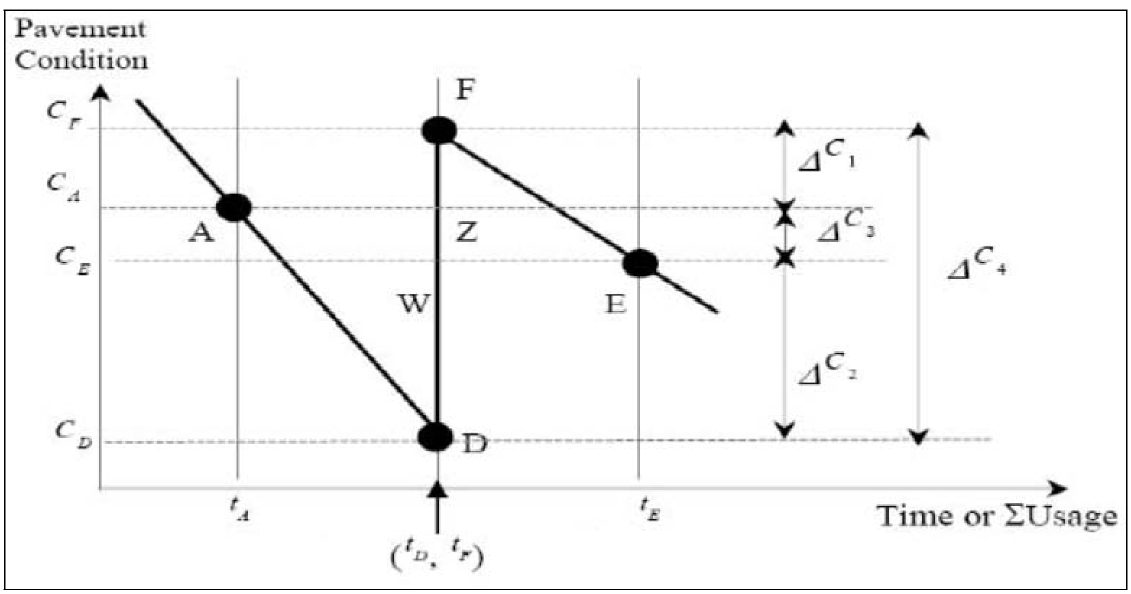

Figure 2.5 Measuring short-term effectiveness: Deterioration reduction concept (Source: Labi and Sinha, 2003a)

It has been shown (Labi and Sinha, 2003a, 2004) that using $DRL_{Type\ I}$ underestimates effectiveness because it fails to consider the pavement condition at a point in time just before treatment. Thus it does not capture the effectiveness of maintenance or rehabilitation in recovering the pavement condition (from point D to point Z). In a similar context, DRL Types II and III also underestimate the maintenance or rehabilitation effectiveness. Type II does not account for the pavement condition right after treatment, and the maintenance or rehabilitation effectiveness in recovering the pavement condition (from point W to point F) is missed. In Type III, maintenance or rehabilitation effectiveness is likely to be negative if this measure is used; something that may mislead to the conclusion that treatment is not effective. The DRL Types can be expressed as follows (Labi and Sinha, 2003a):

- As a simple difference (or an absolute change) between two measurements in time relative to the oldest measurement (e.g., ΔPSI = change in PSI);
- As a ratio of the change to the initial condition (e.g., Δ PSI / initial PSI);
- As a percentage change relative to the initial condition (e.g., [ΔPSI / initial PSI] × 100).

In past studies (Li and Sinha, 2000; Madanat and Mishalani, 1998; Fwa and Sinha, 1986, 1987 and 1991; Sinha et al., 1988), DRL has been widely used as a short-term maintenance or rehabilitation effectiveness measure. Models predicting the PSI change or change in roughness as a function of pavement attributes, climate, unit expenditure, and maintenance or rehabilitation have been developed.

The performance jump (PJ) is computed using deterioration values just before and right after treatment, and is identified as the instantaneous (or vertical) elevation in the pavement condition due to treatment (see ΔC4 in Figure 2.5). In past research (Markow, 1991; Rajagopal and George, 1990; Mouaket et al., 1992; Lytton, 1987; Labi et al., 2007; ColluciRios and Sinha, 1985) the performance-jump concept has been widely used. When treatment deterioration just before and right after values are included, the PJ measure offers a solid way of short-term assessment of maintenance or rehabilitation effectiveness, by accounting for the time-related problems of the DRL measure. As expected, the shorter the treatment activity duration and the smaller the time between deterioration measurements and treatment, the more accurate the performance jump values are. However, data for the performance-jump computation is very difficult to obtain because road agencies typically do not measure deterioration just before and right after treatment. To obtain performance-jump values, Labi and Sinha (2004) suggest extrapolating the performance curve from both directions to the point of treatment. For the cases where the just-before and right-after measurements of deterioration are obtained, relative timing between deterioration measurements and treatment is a secondary issue with respect to the performance-jump computation. In contrast, when monitoring takes place over large time intervals (e.g., one year), determining whether it occurred before or after treatment is crucial with respect to selecting appropriate performance-jump formula.

The deterioration reduction rate (DRR) can be defined as the pavement deterioration delay (with respect to cumulative loading and time) due to maintenance or rehabilitation, and is computed as the difference in the slope of the deterioration curve before and after treatment. In the DRR context, the effect of the treatment is to change the steep slope associated with a rapidly deteriorating pavement to a gentle slope or even produce a significant flattening or even reversal of direction of the deterioration curve (Labi and Sinha, 2004; Johnson and Cation, 1992).

In Figure 2.6, the DRR is illustrated with respect to a number of pavement conditions and repair actions, assuming linearity over time. It can be observed[8] that if no treatment is performed, new pavements in good condition are assumed to deteriorate in the same rate, whereas old pavements in poor condition suffer relatively higher deterioration rates. Also, note that even after minor maintenance (e.g., crack sealing, shallow patching, etc.), the pavement condition is still expected to deteriorate over time

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[8] Conceptually, the shape of the typical pavement performance curve is used, where little and linear deterioration occurs at the pavement life's initial phases, whereas accelerated rates of deterioration occur as the pavement ages.

but at a lower rate. As shown in the figure, the deterioration curve takes on increasingly positive gradients with increasing levels of pavement maintenance.

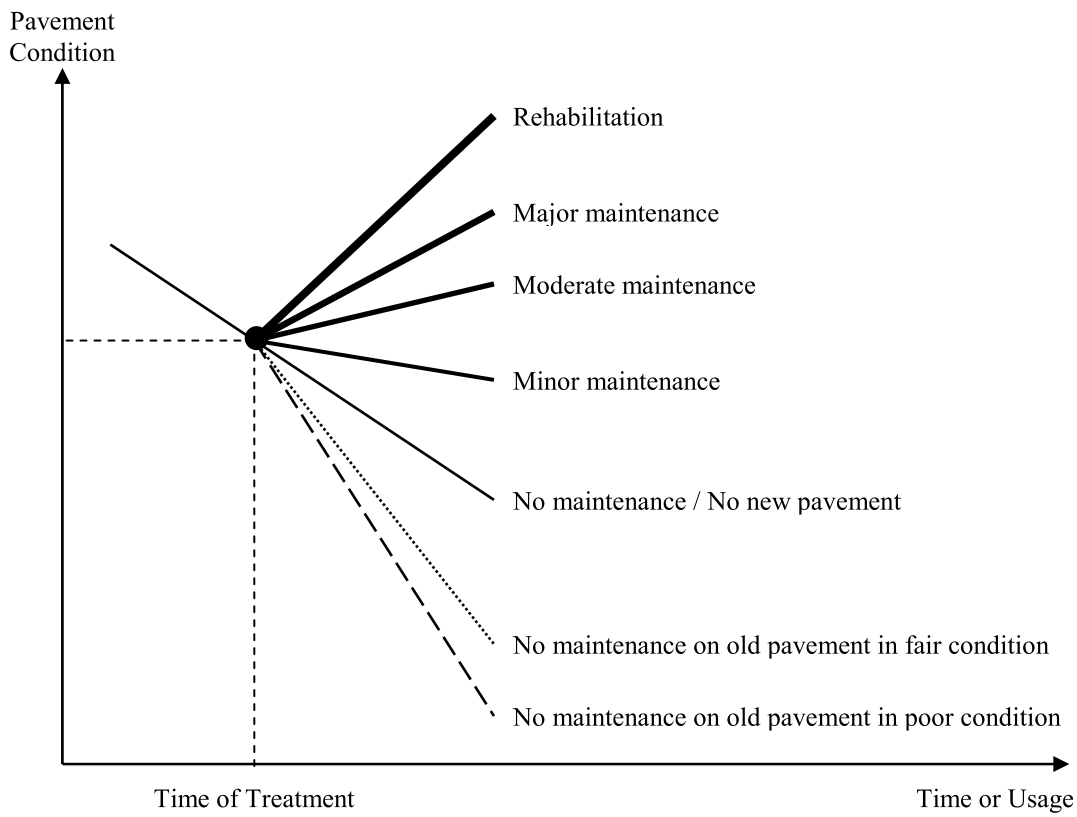

Figure 2.6 Conceptual illustration of deterioration reduction rate (Labi and Sinha, 2004)

According to Lytton (1987) and Markow (1991) the DRR due to specific maintenance or rehabilitation treatments (or combination of treatments) is best determined when no other treatment was applied, so that the effects of such peripheral treatments are averted.[9]

[9] Labi and Sinha (2003c) suggest for the DRR computation that a minimum of three data points in time is recommended.

2.5.2. Long Term Pavement Performance Modeling

Haas et al. (1994) have thoroughly studied several pavement performance indicators and the associated decision criteria for reaching a minimum acceptable limit or 'failure' status, which can then be used as a trigger for maintenance or rehabilitation interventions.[10] They have categorized the pavement performance models into the following groups:

- Purely mechanistic models[11] based on primary response parameters (e.g., deflection, stress, strain, etc.);
- Mechanistic-empirical models based on response parameters related to functional or structural deterioration (e.g., roughness or distress through regression analysis);
- Regression models where the dependent variable of measured or observed functional or structural deterioration is related to one or more independent variables (e.g., pavement layer thickness and properties, environmental factors, axle loads, subgrade strength, etc.);
- Subjective models where 'experience' is captured in a formalized or structured way using transition process models to develop pavement prediction models.

In the United States, the Governmental Accounting Standards Board Statement No. 34 (GASB-34) has introduced, as a fifth category, the straight line depreciation or deterioration performance models based upon financial models (Dewan and Smith, 2005). These models assume that the asset provides equal service to the user for each year of useful life. From the performance modeling perspective, the annual depreciation or deterioration charge is a reduction in the pavement condition. The biggest problem of this model is that it monitors the asset's consumption without acknowledging its good stewardship through timely preventive maintenance.

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[10] Note that pavement safety evaluation based on skid resistance and friction is a major concern in United Kingdom due to the country's predominant wet weather resulting in slippery pavement conditions (Woodward et al., 2002).

[11] Not yet developed, whatsoever.

- Regression models: There has been an abundant amount of research in developing multiple regression analysis techniques. In many studies (Kutner et al., 2004; AASHO, 1962; Watanada et al., 1987; Ferreira et al., 2003; Rauhut et al., 1982; LeClerc and Nelson, 1982; Mahoney and Jackson, 1990; FHWA, 1990; Hajek et al., 1985) regression models using several independent variables to predict pavement condition indexes (e.g., PCR, PSI, etc.) or performance measures have been developed. Some classical deterministic empirical pavement performance models are as follows:

  - AASHO produced the first performance models[12] to predict the number of equivalent single axle loads applications as a function of subgrade strength, layer material properties and thicknesses, drop in serviceability, and environmental factors (AASHO, 1962);
  - The Highway Design and Maintenance Standards (HDM III) performance models[13] were developed by Watanada et al. (1987), and predict the incremental progression of roughness and several distresses on flexible pavements (e.g., cracking, rutting etc.), with respect to subgrade strength, environmental factors, present distress levels, traffic load and time;
  - In the State of Washington Pavement Management System (PMS), nonlinear power function regression models for different pavement types have been developed for network level applications (LeClerc and Nelson 1982; FHWA 1990);
  - In Canada and elsewhere (e.g., pavement function equations for the FHWA cost allocation study have also been developed; see Rauhut et al. 1982), nonlinear regression models for various pavement types with sigmoid (S-shaped) power functions were developed (Hajek et al. 1985).

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[12] These models appear to be more suitable for project level design.

[13] These models have been used for project level design, and in some cases for network level analysis (Ferreira et al. 2003).

Interestingly, some road agencies have also included the effects of pavement performance in the models. For example, Sebaaly et al. (1995 and 1996) developed nine flexible pavement performance models for Nevada that related material properties, traffic loading, environmental conditions and individual districts to PSI. In a similar context, Mohammed et al. (1997) developed models for the State of Indiana to predict performance change as a function of pavement maintenance, traffic, age, etc., and maintenance occurrence[14] (i.e., decision to perform maintenance), while correcting for simultaneity. Using a two-stage approach, the overall fit of the models was very good.

- Mechanistic-empirical models: Mechanistic-empirical models tend to include parameters such as deflection, stress, or strain into the pavement performance model. Queiroz (1983) developed mechanistic-empirical models where linear elasticity was used as the basic constitutive relationship for pavement materials in the study of flexible pavement sections. Calculated responses included horizontal tensile stress, strain, strain energy at the bottom of the asphalt layer, surface deflection, and vertical compressive stress and strain at the top of the subgrade. Mechanistic theories to predict pavement performance, fatigue cracking, thermal (transverse) cracking, and IRI, for flexible and rigid pavements, were used by the proposed mechanistic-empirical pavement design guide (Applied Research Associates Inc., 2004). Numerical optimization and comparison with other models was used to estimate the models.
- Probability-based models: Bayesian and Markov probabilistic modeling approaches are alternatives to the deterministic regression models that do not provide probabilistic distributions of the existing values. Such models have been widely used successfully for network level performance modeling applications. The Bayesian statistical decision theory combines for regression analysis both subjective data from prior knowledge and experience, and objectively obtained actual monitoring data, to predict posterior estimates of pavement condition

[14] In that perspective, a binary logit model was developed.

deterioration. The model parameters in this approach are assumed to be random variables associated with probability distributions (Smith et al., 1979). An application of the Bayesian approach can be found in the Canadian Strategic Highway Research Program (SHRP) studies (Haas et al., 1994). The main advantage is that in contrast with the classical regression analysis, a comprehensive historical database is not needed. For network level applications where historical databases and reliable regression equations are not available for performance predictions, Markov transition probability models are very useful. By using different combinations of pavement classes or situations and condition states, they capture the experience of engineers or experts in a structured way (for example see Finn et al., 1974; Cook and Lytton, 1987; FHWA, 1990; Haas et al., 1994). Advantages of the Markov models include: (a) using the judgment of experienced engineers to develop transitional probabilities for the modeling process; (b) a probability distribution of the expected value of the dependent variable indicating sections with different future performances; (c) consideration of performance trends from field observations regardless of nonlinear time-trends, and (d) an easy way to incorporate field measurements feedback into prediction models. The main disadvantage is that there is no guidance to the physical causes for the pavement condition deterioration, and no consideration of pavement aging on transitional probabilities (Finn et al. 1974; FHWA 1990). The primary application of this approach is the maintenance, rehabilitation and reconstruction (M, R&R) decision-making process at the network level. The PAVER and MicroPAVER software programs allow the prediction of future pavement conditions at any point in time based on a 'pavement family[15] relationship' developed from the measured performance of local pavements (Shahin and Walther, 1990). The prediction function for a pavement family represents the average behavior of all sections of that family. Comparing the section to the family deterioration provides feedback on the effects of

[15] A pavement family is defined as a group of pavement sections with similar deterioration characteristics (e.g., all thin asphalt pavement sections with similar traffic volumes).

maintenance, drainage, traffic, and other factors on the pavement behavior. The family-curve method allows for continuously updating the deterioration model as more data are incorporated into the database.

- Artificial neural network modeling: Using parallel computations for knowledge representation and information processing, Artificial Neural Network (ANN) modeling has gained in popularity. ANN is a powerful data-modeling tool that is able to capture and represent complex input/output relationships. The motivation for the development of neural network technology stemmed from the desire to develop an artificial system that could perform 'intelligent' tasks in information processing, similar to those performed by the human brain. Typically, an ANN consists of a network of nodes that are connected by weighted links. These weighted links establish the relationships between the nodes. Each node sums the weighted inputs entering it and compares the result to a (typically) nonlinear function to produce its own output. Most neural networks have a training rule establishing how the weights are adjusted to bring the average output closest to the desired one (for more information see the ANN related literature including: Ghaboussi, 1992; Hudson et al., 1997; Attoh-Okine, 1998 and 2000). Hence, the ANN model does not execute a series of fixed instructions like a traditional computer program or statistical analysis. Instead, it responds, in parallel, to the inputs presented to it during a training period. According to Ghaboussi, (1992) the major variables of a neural network are the number of nodes and their connectivity (network topology), the rules of computation of the activations of the processing units, the rules of propagation, and the rules of self-organization and learning. ANN models are capable of learning complex, highly nonlinear relationships and associations from a large body of data, such as pavement-management system (PMS) databases. However, neural networks do not give explicit knowledge representation in the form of rules, or some other easily interpretable form. The neural-network model is implicit, hidden in the network structure and optimized weights, between the nodes.

2.5.3. Review of Past Work in Pavement Performance Modeling

Past research efforts have used a wide variety of methodological approaches to analyze pavement performance, maintenance and rehabilitation. Butt et al. (1987) developed a pavement performance and future condition prediction model based on Pavement Condition Index (PCI) and the age of the pavement, using homogeneous and non-homogeneous Markov chains. Smith et al. (1997), using time-series analysis, found that the initial pavement smoothness has a significant effect on the future smoothness of the pavement in both new and overlay construction, and that the added pavement life could be obtained by achieving higher levels of initial smoothness.

Based on the authors' experiences, a framework was developed for a process that can be used for the selection of proper maintenance strategies (crack seals, fog seals, slurry seals, microsurfacing, chip seals, thin asphalt concrete overlays, and other thin surface treatments) for different distress types (roughness, rutting, fatigue cracking, longitudinal cracking, raveling, weathering, and bleeding) in asphalt pavements, depending on environment and traffic volume (Hicks et al., 1997).

Galehouse (1998), designed a preventive maintenance program for the Michigan Department of Transportation, to protect pavement and bridge structures, slow the rate of deterioration, and correct minor pavement deficiencies using surface treatments that primarily target pavement surface defects caused by the environment and deficiencies in pavement materials. The introduction of warranty specifications for all surface treatments is a key finding in his study. Singh et al. (2007) used pavement data from Indiana, to evaluate the costs, effectiveness, and cost-effectiveness of warranty and traditional contracts. Warranty contracts generally were found to have higher agency costs but produce pavements with superior condition and service life, and lower construction periods and work-zone user costs, compared to their traditional counterparts.

Labi and Sinha (2003b) demonstrated a cost-effectiveness evaluation of various levels of preventive maintenance activities over the pavement life-cycle, using performance curves. It is shown that increasing preventive maintenance is generally associated with increasing cost effectiveness, and that interstate pavements and rigid pavements are generally associated with greater resilience to preventive maintenance, compared to their non-interstate and flexible counterparts, respectively. Jackson et al. (1996) also developed pavement performance curves for various new pavement sections as well as for a range of rehabilitation treatments, by using both individual and composite pavement indexes, for use in the enhanced South Dakota pavement management system. The study is based on pavement experts' opinions. In another study, Pavement Condition Rating data from North Carolina were used, for pavement performance prediction, using cycles of decline and improvement in the ratings (Chan et al. 1997).

Shober and Friedrichs (1998) developed a comprehensive Pavement Preservation Strategy (PPS) for Wisconsin, considering all pavement management activities (from "do nothing" to reconstruction). The proposed PPS is cause-based (instead of a schedule-based strategy applying treatments on a predetermined schedule), treating the worst pavements first.

Von Quintus et al. (2007) established and monitored HMA test sections to determine their performance characteristics, and develop improved design methodologies for the Long-Term Pavement Performance (LTPP) program. Using survivability analyses, six distress types are used (fatigue cracking, longitudinal cracking in the wheel path, longitudinal cracking outside the wheel path, transverse cracking, rutting, and smoothness-IRI) to predict the pavement service lives.

Recently, Puccinelly and Jackson (2007) investigated the effect of two types of frost exposure (deep frost penetration, present throughout the winter months, and freeze–thaw cycling, occurring multiple times during the winter) on pavements. To evaluate the effects of the freezing conditions on long-term pavement performance, performance multivariate regression models are developed to compare predicted fatigue, rutting, and roughness measures in different environmental settings. Interestingly, the results show significant differences among the various climatic scenarios.

2.5.4. Pavement Condition Indicators

Among the many indicators that measure the pavement performance, there are four that are typically used in most studies: roughness, pavement condition rating, rut depth, and surface deflection (which is utilized for structural treatments only). In this study, those four are also assumed to be representative of the condition of the pavement:

- The International Roughness Index (IRI) measures irregularities that can result from rutting, potholes, patching and other factors. The IRI is used to define a characteristic of the longitudinal profile of a traveled wheel track and its units are inches per mile or meters per kilometer. The IRI is based on a filtered ratio (referred to as the average rectified slope) of a standard vehicle's accumulated suspension motion (usually in meters or inches) divided by the distance traveled by the vehicle during the measurement (usually a kilometer or mile). In Indiana, the IRI is measured in inches/mile, with lower values indicating a smoother pavement (see Noyce and Bahia (2005) and Shafizadeh and Mannering 2003).

- A rut is defined as a depression or groove worn into the pavement by the travel of wheels (i.e., differences in elevation on the pavement surface across the wheel path). Typically it is measured in inches. Excessive rutting can contribute to vehicle tracking and loss of control during maneuvering (Anastasopoulos et al., 2008).

- The Pavement Condition Rating (PCR) is based upon visual inspection of pavement distress. Although the relationship between pavement distress and performance is not well defined, there is general agreement that the ability of a pavement to sustain traffic loads in a safe and smooth manner is adversely affected by the occurrence of observable distress. The rating method provides a procedure for uniformly identifying and describing, in terms of severity and extent, pavement distress. The mathematical expression for PCR provides an index (ranging from 0 (poorest pavement condition) to 100 (excellent pavement condition)) reflecting the composite effects of varying distress types, severity, and extent upon the overall condition of the pavement.

- Pavement surface deflection is used to evaluate the flexible pavement structure and the rigid pavement load transfer. It is an important pavement evaluation method because the magnitude and shape of pavement deflection is a function of pavement structural section, traffic (type and volume), temperature and moisture affecting the pavement structure. Surface deflection is measured as a pavement surface's vertical deflected distance as a result of an applied static or dynamic load. The most common type of equipment to measure the surface deflection is the falling weight deflectometer (FWD). The units for the surface deflection used in the analysis are thousandths of inches (or mils) from a FWD center-of-load deflection, corrected to a 9,000 lb. load applied on a 11.8-inch diameter plate, adjusted for temperature (65 degrees Fahrenheit). From this point, surface deflection will be abbreviated with FWD.

2.5.5. Pavement Performance Thresholds

The 1998 FHWA strategic plan (FHWA, 1999) defined a qualitative pavement condition term and the approximate corresponding quantitative PSR or IRI values, along with the FHWA descriptive term for pavement condition 'acceptable ride quality'. Pavement performance should have an IRI value of less than or equal to 170 in/mi (2.7 m/km), to be rated acceptable. Table 2.3 summarizes the Federal pavement roughness thresholds for interstate facilities as presented in the 1998 FHWA strategic plan.

Table 2.3 Federal pavement roughness thresholds for interstate facilities
(Source: FHWA, 1999)

Condition Term	PSR	IRI (in/mi)	IRI (m/km)	NHS Ride
Very Good	>=4.0	<60	<0.95	Acceptable: 0-170
Good	3.5-3.9	60-94	0.95-1.48	
Fair	3.1-3.4	95-119	1.50-1.88	
Mediocre	2.6-3.0	120-170	1.89-2.68	
Poor	<=2.5	>170	>2.68	Less than Acceptable: >170

Flintsch and Zaniewski (1997) used artificial neural network (ANN) modeling to develop an automatic project recommendation procedure for Arizona Department of Transportation (ADOT), to reduce the effort required to develop preservation programs. Roughness (maysmeter; see Meyer and Reichert, 1990), cracking (%), rutting (inches), patching (%), and maintenance cost (USD) threshold values for interstates and non-interstates were determined on the basis of the opinions of nine ADOT experts (at which levels of the various condition indicators pavements were considered in need of a preservation treatment). The average roughness (for interstates 105 in/mi, for non-interstates 142 in/mi) and cracking (for interstates 12 mm, for non-interstates 18 mm) threshold values were used for the remaining service life calculations.

Lamptey et al. (2005) developed preservation strategies for INDOT to ensure long-term and cost-effective pavement investments, using pavement condition thresholds and predefined time intervals (based on treatment service lives). The development of rehabilitation and maintenance strategies is based on INDOT and Purdue University pavement experts, INDOT’s Pavement Design Manual Chapters 52 and 56, and condition/performance triggers established in other State highway agencies for application of rehabilitation and maintenance. Table 2.4 summarizes the determination of the levels at which specific treatments are applied based on plots of historical performance/condition involving IRI, rutting and cracking; whereas, Table 2.5 summarizes the results of the survey, the INDOT pavement condition manual, and the historical plots and summarized charts for National Highway System (NHS) Interstates, NHS non-Interstates, and non-NHS non-Interstates.

Table 2.4 Temporal trends in trigger values (mean values from Lamptey et al., 2005)

	IRI (in/mi)	**RUT (inches)**	**PCR**
Surface Treatment, PM	106.79	0.09	92.94
HMA Overlay, PM	110.81	0.24	89.65
HMA Overlay, Functional	95.90	0.20	84.52
HMA Overlay, Structural	102.32	0.20	90.62
Resurfacing (Partial 3R*)	130.86	0.22	88.17
Crack & Seat and HMA Overlay	121.12	0.20	84.52
Rubblize & HMA Overlay	131.74	n/a	80.10
Pavement Rehabilitation (3R/4R**)	116.03	0.23	88.91
Pavement Replacement	102.11	0.11	95.44

* 3R: resurfacing, restoration and rehabilitation

** 4R: resurfacing, restoration, rehabilitation and reconstruction

Table 2.5 Historical trigger values (mean values from Lamptey et al., 2005)

	NHS Interstates								
	IRI (in/mi)			**RUT (inches)**			**PCR**		
	Rigid	Asphalt	Asphalt-over-Rigid Composite	Rigid	Asphalt	Asphalt-over-Rigid Composite	Rigid	Asphalt	Asphalt-over-Rigid Composite
Resurfacing (Partial 3R Standards)	98.33	82.92	86.07	0.09	0.09	0.18	93.06	95.51	90.31
Pavement Rehabilitation 3R-4R Standards	104.58	114.69	104.80	n/a	0.13	0.16	n/a	90.53	94.67
	NHS Non-Interstates								
	IRI (in/mi)			**RUT (inches)**			**PCR**		
	Rigid	Asphalt	Asphalt-over-Rigid Composite	Rigid	Asphalt	Asphalt-over-Rigid Composite	Rigid	Asphalt	Asphalt-over-Rigid Composite
Resurfacing (Partial 3R Standards)	102.77	102.63	122.50	0.23	0.09	0.20	89.95	93.19	89.00
Pavement Rehabilitation 3R-4R Standards	88.59	147.92	112.28	0.17	0.29	0.22	92.50	81.66	91.38
	Non-NHS Non-Interstates								
	IRI (in/mi)			**RUT (inches)**			**PCR**		
	Rigid	Asphalt	Asphalt-over-Rigid Composite	Rigid	Asphalt	Asphalt-over-Rigid Composite	Rigid	Asphalt	Asphalt-over-Rigid Composite
Resurfacing (Partial 3R Standards)	112.82	124.13	131.30	0.23	0.09	0.23	89.78	91.59	84.75
Pavement Rehabilitation 3R-4R Standards	119.49	140.17	136.67	0.25	0.13	0.16	90.24	83.95	87.42

* 3R: resurfacing, restoration and rehabilitation

** 4R: resurfacing, restoration, rehabilitation and reconstruction

Labi et al. (2005) determined long-term effectiveness of thin HMA concrete overlays by using, as measures of effectiveness the treatment service life, the increase in average pavement condition, and the area under the performance curve, with pavement performance indicators the IRI, rutting, and PCR. The pavement condition thresholds used (for Interstates: IRI 73.66 in./mi, rutting 0.17 in, PCR 87.86; for non-Interstates: IRI 102.23 in/mi, rutting 0.165 in, PCR 94.55) are an average of historical thresholds at which thin HMA overlays have been applied.

Shober and Friedrichs (1998) presented a pavement evaluation strategy that provides a logical approach to progressing from field observations of distress to proposed treatment strategies. The pavement condition thresholds identified for road functional class and action type (see Table 2.6), are used as a comparison basis for evaluating the aggregated ratings for ride (pavement terminal/serviceability index (PSI), distress (using the pavement distress index (PDI), and rut depth (RUT).

Table 2.6 Pavement thresholds (Source: Shober and Friedrichs, 1998)

Highway Classification	**Action Type**					
	Should			**Must**		
	PSI	**PDI**	**RUT**	**PSI**	**PDI**	**RUT**
Interstate, Principle Arterial	2.75	65	9mm	2.25	85	15mm
Minor Arterial, Major Collectors	2.25	70	13mm	1.75	90	19mm
Minor Collectors, Local Roads	1.75	80	13mm	1.50	90	19mm

Hicks et al. (2000), developed methodologies for maintenance treatment selections on interstate and primary highways for the Pavement Management System (PMS) of Montana Department of Transportation. The pavement condition thresholds used and suggested treatments, are presented in Table 2.7.

Table 2.7 Decision table for maintenance treatments on interstate and primary highways from Montana DOT – PMS[16] (Source: Hicks et al., 2000)

Maintenance Treatment	**Ride**	**SCI**	
Do Nothing	>73		
Thin Overlay	60-73	>60	
Thin Overlay, SR		<=60	
Reactive Maintenance	<60		
Maintenance Treatment	**ACI**	**AGE**	**SCI**
Do Nothing	>90		
Crack Seal and Seal & Cover	81-90	>6	
Crack Seal		<=6	
Thin Overlay	66-80		>60
Thin Overlay, SR			<=60
Reactive Maintenance	<66		
Maintenance Treatment	**MCI**	**AGE**	**SCI**
Do Nothing	>94	>12	
Crack Seal and Seal & Cover		7-12	
Do Nothing		<7	
Crack Seal and Seal & Cover	71-94	>6	
Crack Seal		<=6	
Thin Overlay	56-70		>60
Thin Overlay, SR			<=60
Reactive Maintenance	<56		
Maintenance Treatment	**Rut**	**Ride**	**SCI**
Do Nothing	<0.41		
Maintenance Rut Fill	0.41-0.52	>60	>60
Reactive Maintenance			<=60
Reactive Maintenance		<=60	
Reactive Maintenance	>0.52		

Ksaibati et al. (1996) evaluated surface treatment practices in several states in the United States. The pavement performance indicator used is the skid resistance, and summarized results are presented in Table 2.8.

[16] Note that the SCI refers to the surface condition index (measured on a 0-100 scale), the ACI to the alligator cracking index (measured on a 0-100 scale), the MCI to the miscellaneous cracking index (measured on a 0-100 scale), and Ride to ride quality (measured on a 0-100 scale). Rut is measured in inches.

Table 2.8 Skid number thresholds for rehabilitation[17] (Source: Ksaibati, et al., 1996)

SN40 Thresholds	State Highway Agency
<=43	AZ
<=40	ID, NC*
<=39	NE
<=37	NV, OR
<=35	MD, MS, OH, UT, WY
<=30	IN
<=25	WA

* Skid Number was measured at 45 miles per hour.

Reigle (2000) developed a probabilistic model that derives flexible pavement designs, generates preservation strategies, and evaluates the life-cycle costs of each alternative. Functional aspects (structural capacity and pavement condition) and safety (skid resistance) are incorporated into the design, rehabilitation and preventive maintenance as preservation strategy alternatives are included in the model, and agency and user cost are considered in the present worth cost analysis. As pavement condition thresholds, the PSI (the default value is 2.0, and the maximum allowable value is 3.0), the PCR (55), and the SN40 (the default value is 32, and the maximum allowable value is 38) are used.

Recently, Labi and Sinha (2007) developed a methodology to identify the optimal period between reconstruction projects for infrastructure systems with pavement (or bridge) condition stochastically deteriorating over time. Time-based thresholds are considered; that is, a road agency aiming to undertake reconstruction projects after fixed intervals in time is assumed, and the fixed interval width that maximizes cost effectiveness is estimated through numerical algorithms.

[17] The skid number (SN) is typically measured using a locked-wheel skid trailer operated in accordance with ASTM E-274 (Reigle, 2000; Reigle and Zaniewski, 2002b); when the skid testing is conducted at 40 miles per hour, the result is referred to as SN40. Instead of SN, friction number (FN) is typically used. Threshold values for minimum acceptable skid number, varies between state highway agencies.

A number of studies (Nair et al., 1985; Khattak et al., 1993; Ng et al., 1995; Kuemmel et al., 2001a, 2001b, 2001c; Shafizadeh et al., 2002) have determined pavement condition thresholds based on the users opinion (using surveys). For example, Shafizadeh and Mannering (2003) investigated the driving public's attitude toward acceptable levels of road roughness by matching individual driver acceptability levels with the federal IRI guideline of 170 in/mi (2.7 m/km), to examine the existence of potential user acceptability thresholds on urban highways. The findings of this research provide empirical support for the federal IRI guidelines.

2.6. Evaluating Cost Effectiveness of Pavement Treatments

Cost effectiveness evaluation (CEE) is a short-term[18] or long-term[19] economic evaluation analysis that compares and evaluates the relative expenditure and outcomes (e.g., benefits, returns, or progress towards stated objectives, etc., regardless whether the outcome can be monetized) of two or more alternative courses of action (Labi, 2001).[20] In CEE, even if expenditure (i.e., costs) cannot be put in terms of dollar amounts, its effectiveness (i.e., reaching desirable results and goals) is quantitatively described (Mouaket and Sinha, 1990). Chong (1989) expressed the need to quantify the effectiveness of treatment, the extension of pavement remaining service life and the influence of treatment time, and discussed critical issues addressed by pavement maintenance and rehabilitation treatments CEE. These critical issues included: delays in pavement deterioration due to treatment; changes of the existing pavement due to maintenance treatment; and the optimal time when there is a specific distress condition or progression to apply the most cost effective treatment. There are three methods to conduct CEE; the maximum benefit approach, the least life-cycle cost approach, and a combination of the two.

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[18] For example, cost effectiveness evaluation of different pavement maintenance or rehabilitation treatments performed at a given, relatively small time period.

[19] For example, cost effectiveness evaluation of a large number of pavement maintenance or rehabilitation treatments performed over the pavement's service life, or over an extended, relatively large time period.

[20] Typically, CEE is more appropriate for long-term purposes (see Labi, 2001).

2.6.1. Maximum Benefit Approach

This approach seeks to maximize benefits for a given investment level, and is typically used for capital investment decisions (Mouaket and Sinha, 1990). In pavement management, benefits are expressed in terms of the use of the extension of the remaining service life of the pavement by carrying out a set of improvements or treatments, or by the area under the performance and time curve (Sinha and Labi, 2007). With respect to the second case, a well-treated pavement with a low deterioration rate and large area under the performance curve provides greater user benefits than a poorly-treated pavement. The area under the performance curve is used as a surrogate measure because the performance is difficult to be quantified in monetary terms. Benefits may also include (Geoffrey 1996): (a) reductions in the rate of pavement deterioration; (b) deferred (or reduced) capital expenditure through preservation of capital; (c) reductions in vehicle maintenance and operating cost; (d) an increase in safety and comfort for the motorists; (e) reductions in travel time; and (f) reductions tort liability.

- Quantifying benefits using the extension of the remaining service life: The remaining service life (the time for the pavement to deteriorate until the allowable serviceability threshold) is a means of quantifying the benefits (i.e., extension of the remaining service life) associated with pavement maintenance or rehabilitation treatments, using pavement performance models.

- Quantifying benefits using the area under the performance-time curve: There are two approaches: (i) a quantitative performance measure is developed to compare different overall pavement performances in various strategies (Fwa and Sinha, 1986 and 1991), and (ii) quantitative values of user benefits for different pavement serviceability levels are established.

- Quantifying Agency and User benefits: To quantify the Agency benefits, the pavement performance quality index (PQI) is an aggregate representation of the overall performance of a pavement (for the considered analysis period). It has been found (Cummings et al., 1986; Cox, 1986) that the willingness-to-pay approach (obtained by expressed (e.g., surveys, interviews, etc.) or revealed (e.g., individual actions are assumed to reveal the preferences that motivate them) preference methods) is the most appropriate for benefit assessment. Using the expressed preference approach, road-agency benefits can be evaluated through surveys and/or interviews with officials involved in decision making. Pair-wise comparisons of hypothetical strategies bearing different agency costs and PQI values[21], can be performed by each decision maker who is asked to favor the optimal strategy. Since, as expected, the results will differ among agencies, due to differences in policies and philosophies, each agency needs to evaluate and obtain its own monetized pavement performance values that reflect its planning and decision making criteria. With respect to quantifying user benefits, the suitable approach for evaluating the monetary values associated with different levels of pavement serviceability is again the expressed preference. The same descriptions for different pavement serviceability levels (used in subjective rating surveys of pavement serviceability) can be used in the benefits-assessment survey (Carey and Irick, 1960). Using willingness-to-pay for the provided level of service, users' values for higher pavement rideability quality can be measured (for example see Sinha and Labi, 2007).

2.6.2. Least (Life-Cycle) Cost Approach

Life cycle cost analysis, as a concept of cost and management accounting, became popular in the 1960s when the U.S. government used it to improve equipment procurement cost effectiveness. From that point, and particularly after the development of the project-level pavement design systems in the 1970s, the concept has spread to pavement design procedures (Haas and Hudson, 1978), with its significance for pavement surface type selection and thickness being recognized in the 1980s (Peterson, 1985; AASHTO, 1986). There are two popular approaches to life cycle cost (Darter et

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[21] Lower agency costs will be associated with lower PQI values.

al., 1987; Chong and Phang, 1988; Sharaf et al., 1988): (i) the least present worth life cycle cost, and (ii) the least annualized life cycle cost, calculated in perpetuity. In Indiana, Mouaket et al. (1992) used life cycle costing to evaluate the cost-effectiveness of chip and sand sealing activities.

The least life cycle cost approach seeks to minimize cost through an effective solution, and is typically used for evaluation of maintenance or rehabilitation treatment decisions. Several alternatives for resurfacing existing pavements, pavement restoration, maintenance and rehabilitation cycles, and pavement maintenance peripheral activities are considered when the life-cycle cost method is applied (Fwa and Sinha 1991; FHWA, 1998; Uddin, 2002). The scheduling of competing maintenance, rehabilitation and reconstruction alternatives may be scheduled as user-inputs, or the results of condition-responsive maintenance, rehabilitation and reconstruction policies (Uddin et al., 1987). The condition-responsive maintenance, rehabilitation and reconstruction policies require pavement-performance models to predict the time and type of the treatment during the pavement service life, by specifying a desired minimum level of serviceability at which an appropriate treatment-action is triggered. As expected, the criteria used to set the serviceability threshold(s) differ with the functional class (rural/urban arterials, collectors, local roads, etc.) of the roadway and across agencies.[22]

Examples of where life-cycle cost methodologies have been applied, include: (a) the probabilistic analysis developed in West Virginia (Reigle and Zaniewski, 2002a); (b) the analysis procedure of calculating work zone user costs in Japan (Taniguchi and Yoshida, 2003; FHWA, 1998); (c) the World Bank's HDM III (asphalt and gravel roads) and HDM4 (concrete, asphalt, and gravel roads) programs used for project- and network-level (Watanatada et al., 1987; HDM, 2002); (d) the Washington program implemented in the project-level pavement investment decision program, where deterministic dynamic

[22] For example, on urban highways a PSR or PSI value of 2.5 can be used to determine the time to initiate rehabilitation; whereas, on rural highways and low-volume roads, a threshold value of 1.5 can be used (Uddin et al., 1987). These minimum acceptable values depend on what the agency can afford and the public (i.e., users) is ready to accept.

programming is used for treatment selection (Papagiannakis, 2003); (e) the USER LCC analysis program (Uddin 1993, 2002) which incorporates condition deterioration models for asphalt and concrete pavements, the FHWA vehicle operating cost models (Zaniewski et al., 1982); and (f) the Planning and Budget Analysis of Maintenance program for network level analysis in Mexico (Uddin and Torres-Verdin, 1998).

2.6.3. Combination of Maximum Benefit and Life-Cycle Cost Approaches

It is apparent that rehabilitation can be evaluated with the maximum-benefit approach, and corrective maintenance with the least-cost approach. However, for preventive maintenance a combination of both approaches may be more appropriate, due to its nature and objectives (Labi, 2001; Geoffrey, 1996; Fwa and Sinha, 1991).

2.7. Decision Criteria for Maintenance, Rehabilitation and Reconstruction

Pavement-condition deterioration results in increased user costs and public complaints. Decision criteria and policies for maintenance, rehabilitation and reconstruction alternatives selection (in a timely manner) need to be established in pavement planning, design, construction, research, evaluation, and maintenance. Therefore, pavement -condition data analysis in the network needs to be followed by the maintenance, rehabilitation and reconstruction alternatives selection and their analysis in terms of related costs for all candidate pavement sections. Database tables, steps and guidelines in this analysis typically involve policies (scope of application, section area, related condition data, executive priority criteria, etc.), decision criteria[23], treatment catalogues (e.g., types of

[23] These criteria can also be global (analysis period, discount rate, inflation rate, analysis year, budget constraints, etc.), and typically involve pavement condition parameters for the network level analysis (rutting, roughness, structural condition, geometric deficiencies, severity and extent of distresses, loss in skid resistance or friction, noise, etc.), minimum acceptable condition for selected attributes for different functional classes, traffic levels, etc., capital improvement needs (upgrade to a higher functional class, number of lanes increase, etc.), and other executive priority criteria (safety, emergency based on accidental or natural disasters, urgency, overall budget constraints, etc.).

treatment and their effects on pavement condition, unit costs, productivity as required in the agency work performance standard, etc.), pavement condition performance and deterioration models, input data for user cost analysis for routine maintenance, as well as short- and long-term maintenance, rehabilitation and reconstruction alternatives (Uddin, 2006). Note that the last two database table types provide inputs for both network and project level analysis.

Appropriate policies that identify specific treatments associated with intervention levels of pavement condition attributes for candidate sections are established to recognize the selection needs of pavements including routine and minor maintenance or global major maintenance, rehabilitation and reconstruction strategies, and develop PMS and related application tools (i.e., software). Policies and methods for treatment selection typically include life-cycle cost and benefit analysis (considering roughness and distress attributes for interventional levels and selection of the most economical one), composite indexes (e.g., PQI as a function of IRI and distress attributes), distress type and severity analysis (e.g., PAVER software procedures), artificial intelligence applications (e.g., artificial neural networks, fuzzy logic and knowledge-based expert systems[24], etc.), decision tree analysis (considering distress type and other condition attributes), and *ad-hoc* analysis (based on subjective preference or judgment, past experience, etc.), (Shahin and Walther, 1990; Uddin, 2006).

Although these policies are widely implemented, there are some flaws. For example, decision tree analysis is the most popular approach, but if other pavement condition attributes besides distress are considered (e.g., IRI, deflection, etc.), it becomes very complex (Fwa, 2006; FHWA, 1990). Moreover, the traditional *ad hoc* policy was the norm before the comprehensive pavement management systems. However, using

[24] In traditional knowledge-based expert systems (KBES), a knowledge base is developed and problems are solved through simple decision rules by experienced pavement engineers who use their judgment to select appropriate strategies. Fuzzy logic systems are an extension of KBES, and especially useful for the decision-making process combined with descriptive rules through fuzzy logic (Fwa and Chan, 1993; Haas et al., 1994; Fwa and Shanmugam, 1998).

only a few of the composite indexes in pavement management system (PMS) programs is an oversimplification because the mechanism leading to condition deterioration may be missed and, consequently, may result in an inappropriate maintenance treatment selection.

Turning to the decision criteria, these are established to identify and schedule pavement sections for a rational maintenance, rehabilitation and reconstruction strategy selection. INDOT's decision criteria typically include:[25]

- Minimum thresholds for geometric deficiencies (drainage, grade and cross fall, etc.), or structural adequacy, or remaining life, or pavement noise, or for other safety indexes (skid resistance, friction, etc.);
- Minimum acceptable serviceability (minimum PSI);
- Maximum acceptable roughness level (IRI);
- Minimum acceptable composite index such as PQI (roughness and distress data);
- Minimum acceptable PCR or maximum distressed area (distress survey data);
- Maximum sensor 1 deflection normalized to a standard peak load and temperature and related deflection basin parameters.

At least one of the aforementioned criteria is essential for network-level analysis, but combinations of two or more criteria are often used in practice. Change in the criteria, policies and methodology will affect the system-generated reports and agency resources. For large networks, the PMS and other highway network elements objectives need to be integrated. Sinha and Fwa (1989) developed an integrated highway management system with a 3-dimensional matrix involving highway facility elements (including pavement, bridge, roadside assets, traffic control devices, etc.), system objectives and operational features, and concluded that this system has to be adjusted to the agency's needs so that no resources are wasted in database management.

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[25] Decision criteria for asphalt surfaced flexible pavement treated with thin hot-mix asphalt overlays (network level) typically include extensive raveling or weathering of the surface, less than 3.0 PSI, less than 0.5 inches rutting, 75 to 85 PCR (with only moderate cracking), preventive maintenance on a lower volume road over existing successive chip seals to restore rideability, etc.

As far as treatment catalogues are concerned, detailed data (typically, including unit costs and expected condition immediately after the treatment, estimate of expected life and years of service before the next treatment, etc.) for each pavement-specific treatment are needed in separate database tables, which are then accessed by the PMS analysis program (for a preservation example see: Uddin et al., 1987; Flintsch et al., 1994). Table 2.9 shows Pennsylvania DOT recommended ranges of various alternatives based on results for asphalt pavements. These results, however, should not be considered transferable to other regions or states, because the estimates are regional and appropriate to specific highway traffic levels (for low volume roads, longer life would be possible). In the State of Arizona, survivor curves have been developed to estimate asphalt pavements overlay life (Flintsch et al., 1994). An example of maintenance catalogue data items for an asphalt overlay alternative is shown in Table 2.10. (Note that PCI is the pavement condition index.)

Table 2.9 Expected life-span of rehabilitation alternatives for asphalt pavements (Source: Uddin et al., 1987)

Rehabilitation Alternative	Expected Life (Years)	
	Low Traffic	High Traffic
Crack sealing	3-5	2-3
Bituminous patching	4-6	3-4
Seal coat	4-5	2-3
Level and seal coat	5-7	2-4
Milling and recycling	7-9	5-7
Thin overlay	5-8	3-6
Thick overlay	9-12	7-10

Table 2.10 Data reference in a typical catalogue table for an asphalt structural overlay of 100 mm thickness (Source: Flintsch et al., 1994)

Pavement Type	Expected Life (years)	Cost		Production Rate per Day (m^2)	Improved Condition			Change in Surface Elevation
		USD	Unit		PSR	IRI (m/km)	PCI	
Flexible (Asphalt)	20	10	m^2	500	4.5	2	100	YES
Composite	15							
Jointed Plain Concrete	10							
Jointed Reinforced Concrete	12							
Continuously Reinforced Concrete	12							

The importance of determining pavement service life subject to various preservation treatments is apparent. Labi and Sinha (2003a and 2003b) summarized preventive maintenance effectiveness on pavement condition and service lives of maintenance treatments in several states (see Tables 2.11 and 2.12). Typical performance lives of various treatments for use in life-cycle cost analysis are defined in Chapter 52 of INDOT's Design Manual (INDOT, 2008), where the design lives (being the estimated service life of the pavement and varying based on engineering judgment of the existing conditions, past performance, or the condition of the drainage system; Lamptey et al., 2005) are recommended for use for the various initial, maintenance, or rehabilitation options as presented in Table 2.13 (Labi and Sinha, 2003a).

Stroup-Gardiner et al. (2007), instead of modeling the type and extent of pavement distresses with age, developed a process that coded the Long Term Pavement Performance (LTPP) DataPave database for the first occurrence of a given distress in each of the test sections. It was found that there was no longitudinal fatigue or transverse cracking present at 3 years; less than 2% of the sections experienced longitudinal fatigue or transverse cracking at 5 years; 3-6% of the sections had longitudinal fatigue or thermal cracking at 7 years; at 15 years approximately 50% of the sections showed signs of cracking distresses; and at 20 years 60-70% of the sections had excessive cracking.

Table 2.11 Preventive maintenance effectiveness on pavement condition (Source: Labi and Sinha, 2003a)

Agency	**Treatment**	**Performance**	**Comments, Source and Reference**
SHRP (SPS-4 Rigid Pavement Test Sections)	Sealing of joints in rigid pavements	Unsealed joints experience more spalling than sealed joints	(Morian et al., 1998) Treatments rather than strategies are being evaluated
	Undersealing and sealing of joints in rigid pavements	No conclusions yet	
	Other preventive maintenance treatments on rigid pavements	Diamond grinding, dowel installation and consistenctly-maintained edges resulted in significantly reduced pumping	
SHRP (SPS-3 Flexible Pavement Test Sections)	Crack sealing	• No treatment-specific observations yet • More cost-effective to carry out PM throughout pavement life • Service life extension can be maximized if PM is carried out on good to fair pavement	(Hanna, 1994) Most test sections have a granular base. Treatments rather than strategies are being evaluated.
	Chip sealing		
	Slurry sealing		
	Thin overlay		
SMERP Program (Texas)	Traditional chip seals	Performance of chip-sealed pavements same for those in good initial condition as those in fair or initial condition	(Syed et al., 1998) Treatments rather than strategies were evaluated.
	ARM chip seals	ARM chip-sealed pavements in good initial condition outperformed those in fair or bad initial condition	
	Fog seal	Fog seals had little or no impact	
	All treatments	PM treatments on pavements in good initial condition generally outperformed those in fair or bad initial condition	

Table 2.11 (continued) Preventive maintenance effectiveness on pavement condition (Source: Labi and Sinha, 2003a)

Agency	Treatment	Performance	Comments, Source and Reference
The Oakland MTC Study	Rejuvenating Seal Slurry Seal Single Chip Seal Double Chip Seal Thin HMAC overlay No PM	• Strategies that did not involve PM were found to be poor choices • Pavement condition at time of PM is a vital factor in cost effectiveness • Average annual maintenance cost is higher in long-term if pavement is allowed to deteriorate	(Darter et al., 1987)
Purdue University	Crack sealing	Increased levels of crack sealing in the Fall season results in significantly decreased re-sources expended on corrective maintenance (patching) in the following Spring Season.	(Sharaf and Sinha, 1986)
The Ontario MTC Study	Various combinations of crack sealing and HMA overlay application intervals, including a “donothing” strategy	In the long run, strategy involving crack sealing every 4 years and thin HMA overlay every 8 years was found to be most cost-effective	(Chong and Phang, 1988) Strategies, rather just treatments, were evaluated.
Wisconsin DOT	Sealing of Joints Non-sealing of joints	• Pavements with unsealed joints performed better than those with sealed joints • Pavements with wide joints outperformed those with narrow joints	(Shober, 1986 and 1997)
The Mississippi Study	Surface treatment Thin HMAC overlay	Pavement condition at time of maintenance has a profound effect on service life	(Rajagopal and George, 1990)
Florida I-10 Study	Stitching of cracks in rigid pavements	• Over 5-year life extension observed & faulting reduced • Retrofit dowels yield higher load transfer than shear devices	(Darter et al., 1994)

Table 2.12 Preventive maintenance effectiveness on pavement condition
(Source: Labi and Sinha, 2003a)

Agency	**Treatment**	**Service Life (approx.)**	**Comments, Source and Reference**
Indiana DOT	Chip seal	4 years average	(Feighan, et al., 1986)
	AC crack seal	2.2 years average	For pavement in good condition
Ontario MTC	AC rout and seal	2-5 years	(Joseph, 1992)
New York State DOT	PCC joint & crack filling	2 years	(New York State DOT, 1992)
	PCC joint & crack sealing	8 years	
	AC rout & crack seal	5 years	
	AC crack filling	2 years	
	Thin overlay	8 years	
	Surface treatment	3 years median	
NCHRP	Chip seal	1-6 years	(Shuler, 1984)
	Slurry seal	1-6 years	
	Micro-surfacing	4-6 years	
	Thin overlay	less than 6 years	
FHWA	Micro-surfacing	5-7 years	(Raza, 1994)
	Slurry seal	3-5 years	
	Thin overlay	8-11 years	
	Chip seal	4-7 years	
Oregon DOT	Chip seal	3-6 years	(Parker, 1993)
U.S. Corps of Engineers	Slurry seal	3-6 years	(Brown, 1988)
	Surface treatment	3-6 years	
	Crack seal	3-5 years	

Table 2.13 Preventive maintenance effectiveness on pavement condition
(Source: Labi and Sinha, 2003a)

Pavement Type	Treatment	Average Age at 1st Application (Years)	Average Frequency of Application (Yearly Interval)	Average Perceived Treatment Life (Years)
Asphalt	Crack sealing	3	4	3
	Chip sealing	7	5	6
	Sand sealing	12	4	5
	Crumb rubber sealing	2	NI	NI
	Micro-surfacing	15	NI	3
	Thin HMA overlay	17	11	11
Rigid	Joint sealing	8	6	10
	Crack sealing	6	4	6
	Under-drain maintenance	1	3	2
Asphalt on rigid - composite	Under-drain maintenance	1	1	2
	Crack sealing	2	3	4
	Chip sealing	10	5	5
	Sand sealing	12	4	5
	Crumb rubber sealing	1.5	NI	NI
	Micro-surfacing	15	NI	3
	Thin HMA overlay	20	11	9

2.8. Maintenance, Rehabilitation and Reconstruction: Ranking and Optimization

An effective maintenance, rehabilitation and reconstruction work program consists of prioritized road lists, which can have a simple (e.g., reduce treatment's present work cost) or complex (e.g., nonlinear mathematical optimization) form. In priority ranking, pavement condition and serviceability indexes, road functional classes, traffic levels, and agency and user costs are typically considered, and are usually subject to the total treatment costs not exceeding a pre-specified budget level. In practice, each road agency formulates its own analytical methods (e.g., condition and/or priority indexes, decision trees, linear and nonlinear mathematical optimization models, etc.), engineering decision criteria and weighing factors for priorities, based on its goals, and the network condition, performance and characteristics. Some procedures and/or methods found in the literature that are typically used for prioritization are include priority ranking procedures, mathematical optimization, Markov probabilistic optimization, heuristic approaches, and artificial intelligence.

- Priority ranking procedures: Common prioritization approaches evaluate inter-project tradeoffs in selecting treatment strategies that are budget-constrained. They are typically used in rehabilitation and PMS maintenance. Interestingly, a non-computer based methodology that does not require exact measures of importance among different impacts, was developed in the 1980s (Harness and Sinha, 1983). In this method, projects are grouped and selected based on the ranks and budget constraints, after individual values for priority evaluation measures are plotted. Haas et al. (1994) identified and compared a number of ranking and other prioritization methods used in PMS such as: (a) single- or multi-year ranking based on condition parameters and traffic, applying economic analysis including present worth cost, benefit cost ratio, etc. (reasonably simple; may be closer to optimal); (b) single- or multi-year ranking based on condition parameters, such as serviceability or distress weighted by traffic (simple and easy to use; may be far from optimal); and (c) single- or multi-year simple subjective ranking of projects based on judgment, overall condition index or decreasing first year cost (quick and simple; subject to bias and inconsistency; may be far from optimal); (d) annual optimization by mathematical programming models for year-by-year analysis (slightly complicated; may be closer to optimal; effects of timing are not considered); (e) near-optimization using heuristics approaches including incremental benefit-cost ratio and marginal cost-effectiveness (simple; suitable for microcomputer environment; close to optimal results); and (f) comprehensive optimization by mathematical programming models (typically maximization of benefits or cost-effectiveness) accounting for treatment timing effects (complex and computationally demanding; can give optimal results).

- Mathematical optimization: In mathematics, optimization refers to the study of problems in which a real function is sought to be minimized, maximized, or equal to a specific value, by systematically choosing the values of real or integer variables from within an allowed set. In PMS, an objective function is defined and the overall cost or benefit-cost ratio is sought to be minimized or maximized, respectively, subject to a number of constraints, aiming to find cost-effective solutions. In words, the goal is to choose the best set of candidate sections based on their performance at a point in time. According to FHWA (1990), optimization should also consider the best treatment timing for the candidate section, and select the best sequence of treatment strategies over several years. Similar to priority ranking, mathematical optimization requires current-condition data on pavement sections at the network level, treatment alternatives and their effect on pavement condition, associated costs, and so on. Approaches typically used to solve problems for true and exact optimal solutions include linear and nonlinear programming, integer programming, and dynamic programming (FHWA, 1990; Zimmerman, 1995; Abaza and Murad, 2007). In the 1980s, Colucci-Rios et al. (1984) developed a multi-year optimization model (i.e., the contract section worth model) which uses weighed reductions in pavement distress (over a five year period) as the measure of effectiveness, to determine the optimal resurfacing priorities in the Indiana’s PMS; whereas, Fwa et al. (1988) performed priority assessment of routine maintenance needs and optimal programming of routine maintenance activities, with integer programming.

- Markov probabilistic optimization: In pavement performance prediction, the probabilistic approach considers uncertainty and is able to consider a large number of alternative treatment strategies. A Markov process is a mathematical model for the random evolution of a memoryless system (conditional on the present state, the system’s future and past are independent - one-step memory). With respect to the pavement performance prediction, this means that the probability that the section makes a transition to a particular condition state in a unit time following a particular action, depends only on the present condition state of the section and the action selected at that time, and not on how the section reached that condition state. With the section continuing to make its annual transitions, various costs are incurred (e.g., treatment costs, user costs during the year following the treatment, etc.), which can be used to compute the total expected present work cost for a given strategy (Sinha and Labi, 2006). Then, the strategy that minimizes the total expected cost subject to selected performance-related constraints such as IRI, PSR, PCI, etc. is sought.[26] State highway agencies in Kansas and Arizona have incorporated in their network level PMS Markov decision processes to produce prioritized work programs (Golabi et al., 1982; FHWA, 1990). However, computationally efficient heuristic approaches have been traditionally implemented more widely than Markov probabilistic optimization, for a number of reasons (FHWA, 1990) which include: (a) it is complex and impractical to find the exact optimal policy solution when Markov probabilistic optimization is used, due to the extremely large number of generated alternative treatments; (b) the mathematical concepts of a Markov decision process may be difficult to explain to decision makers and executive managers, since they are derived from another field (i.e., operations research); and (c) computer memory and software computational limits, constraint the Markov process size.

- Heuristic approaches: These produce near-optimal solutions, are appropriate for large-scale problems, and typically include incremental benefit-cost ratio and marginal cost-effectiveness methods or can be more advanced and base upon artificial intelligence techniques (Markow et al., 1994). A number of road agencies (e.g., North Carolina, Minnesota, Alberta in Canada, etc.) have used heuristic approaches to select treatment strategies (FHWA, 1990; Shahin and Walther, 1990).

- Artificial intelligence: It includes techniques that are particularly appropriate for pavement management (due to uncertain and/or incomplete information) such as ANN, fuzzy logic, and evolutionary computing (including genetic algorithms), and has been used for needs analysis as alternatives to the traditional priority

[26] Alternatively, the expected annual benefit (e.g., in terms of reduced user costs) of operating the section in a given condition state may be estimated, and then maximized subject to budget-constraints.

ranking tools, such as decision trees (Fwa and Chan, 1993; Fwa and Shanmugam, 1998; Flintsch and Chen, 2004), or for pavement maintenance and rehabilitation triggering for probabilistic life-cycle cost analysis (Chen and Flintsch, 2007). Another artificial intelligence technique in pavement management application at the network level is genetic algorithms (they are a search technique used to find exact or approximate "good" solutions to difficult large-scale optimization and search problems, and are categorized as global search heuristics), which is based on the mechanics of natural selection and evolutionary computing used in solving complex optimization problems (Fwa et al., 1994, 1988, 2000; Chan et al., 2003). Genetic algorithms are a particular class of evolutionary algorithms (also known as evolutionary computation) that use techniques inspired by evolutionary biology such as inheritance, mutation, selection, and crossover, and have been widely used in pavement management for network level programming (Chan et al., 1994; Fwa et al., 1994, 1998; Ferreira et al., 2003).

2.9. Key Findings from the Literature Review

Pavement maintenance and rehabilitation have occupied a good deal of attention throughout the world over many years. With respect to pavement management, much of the research to date has been primarily providing a better understanding of which pavement treatment suits best various types of pavement distress. The findings from the review of past work are based on both research and practice, and support the following conclusions.

- Due to increases in traffic and to limited resources, pavements need to last longer. Pavement preservation can provide cost-effective opportunities in this regard. For example, pavement maintenance and rehabilitation can keep the pavement in a serviceable condition, improve the motorists' safety, and result in cost savings for the transportation agencies.

- With respect to pavement management, there are many ways to classify pavement distress, and even more techniques to treat each distress type (for flexible, rigid or asphalt Concrete-on-Portland cement concrete Pavements). However, what is important is to slow down pavement deterioration and reduce costs, which can be accomplished by the implementation of preventive maintenance treatments in an early stage of the pavement's service life.

- Pavement performance modeling can be conducted at a short- or long-term basis. A combination of both short-term and long-term performance modeling techniques may result in better-quality information with respect to the underlying mechanisms of the pavement performance.

- There are a number of ways to evaluate the effectiveness of pavement treatments. For example, the cost effectiveness of pavement rehabilitation treatments can be best evaluated with the maximum benefit approach; whereas, corrective maintenance can be best evaluated with the life-cycle cost approach. A combination of both approaches may be appropriate for preventive maintenance.

- Transportation agencies need to establish decision criteria and policies for the selection of appropriate pavement maintenance, rehabilitation and reconstruction alternatives in planning, design, construction, research, and evaluation. These decision criteria may be different, depending on the priorities and needs of the agency.

- To have an effective pavement maintenance, rehabilitation and reconstruction work program, transportation agencies need to formulate a prioritized pavement-asset list. However, each agency may have its own methods, decision criteria and weighting factors for priorities, based on its goals and the network conditions.

CHAPTER 3. METHODOLOGICAL FRAMEWORK AND DATA

3.1. Overview of the Study Approach

The currently available base of information summarized in the previous section includes a wide assortment of studies ranging from broad to narrow in their application. While interesting, many of these studies are not sufficient by themselves to differentiate the advantages and disadvantages of alternative pavement treatments, and provide an approximation of their service lives. For example, pavement performance modeling studies, particularly with respect to pavement preservation, typically are conducted on a basis of data availability and fail to account for the most appropriate performance indicators. Treating all pavement systems as though all the performance indicators are equally important can potentially lead to biases in the estimates of the serviceability life of the pavement.

Moreover, a high level of complexity in data collection requirements as well as in the existing analytical methods is a common limitation in evaluating the effectiveness of pavement rehabilitation treatments with respect to each treatment's service life. Traditionally the estimation of pavement service lives has been conducted with the use of pavement-performance modeling methodologies, where one or more pavement performance indicators are selected and the rate that each indicator deteriorates over time is investigated separately. The results of this approach do not offer a pavement service life estimate nor do they account for potential simultaneous relationships among the pavement performance indicators. As such, these methods are unlikely to be useful as stand-alone approaches, or be applied at the project level to distinguish between different types and service lives of treatments.

This research study builds on the findings and general principles of prior research, and the limitations of past analytical methodologies to provide a more credible foundation for managing the pavements on the basis of appropriate criteria in an effort to increase the pavement service life. As such, this study expands the existing knowledge base by using rigorous analytical tools to estimate the pavement service life and evaluate the effectiveness of potential rehabilitation treatments.

In particular, six pavement rehabilitation treatments in Indiana are evaluated for various (six) road functional classes on the basis of their service lives. The two functional treatments that are investigated are; two-course hot-mix asphalt (HMA) overlay with or without surface milling, and concrete pavement restoration. The four structural treatments are; three-course HMA overlay with or without surface milling, three-course HMA overlay with crack and seat of Portland cement concrete (PCC) pavement, 3-R (resurfacing, restoration and rehabilitation) and 4-R (resurfacing, restoration, rehabilitation and reconstruction) overlay treatments, and 3-R/4-R pavement replacement treatments. The analysis is conducted for six road functional classes; rural interstates, rural non-interstates of the National Highway System (NHS), rural non-interstates that do not belong in the NHS, urban interstates, urban non-interstates of the NHS, and urban non-interstates that do not belong in the NHS. The international roughness index (IRI), the pavement condition rating (PCR), rut depth (i.e., differences in elevation on the pavement surface across the wheel path), and surface deflection (for the structural treatments) are considered to be the pavement condition indicators that determine the performance of the rehabilitation treatments.

In summary, this study seeks to provide a methodological approach that addresses the following questions:

- How to appropriately select pavement performance indicators?
- How the pavement's condition deteriorates over time (how to forecast the pavement's condition in time)?

- What are the influential factors that significantly affect the pavement's condition?
- How to approximate the pavement service life?

3.2. Analysis Steps

The proposed analysis will assist transportation agency staff to have in-house capability to estimate the service life of alternative treatments for pavement rehabilitation, and make better decisions regarding efficient allocation of resources. The overall framework of the study applied for the evaluation for the pavement rehabilitation treatment's effectiveness on the basis of its estimated service life is illustrated in Figure 3.1. The analysis involves the following steps.

STEP 1. Identify the individual pavement sections that need to be treated. As previously mentioned, the focus is on six treatments; two-course HMA overlay with or without surface milling, concrete pavement restoration, three-course HMA overlay with or without surface milling, three-course HMA overlay with crack and seat of PCC pavement, 3-R and 4-R overlay treatments, and 3-R/4-R pavement replacement treatments.

STEP 2. Make sure that the pavements are specified homogeneously, such that the first time period of the pavement's life is right after treatment, and the last is right before the consecutive treatment. In this case, road sections are divided into one-mile stretch homogeneous roadway sections (defined by roadway geometrics, pavement type, and road functional class). The section-defining information includes shoulder characteristics (inside and outside shoulder presence and width, and rumble strips), pavement characteristics (pavement type), median characteristics (median width, type, condition, barrier presence and location), number of lanes and speed limit.

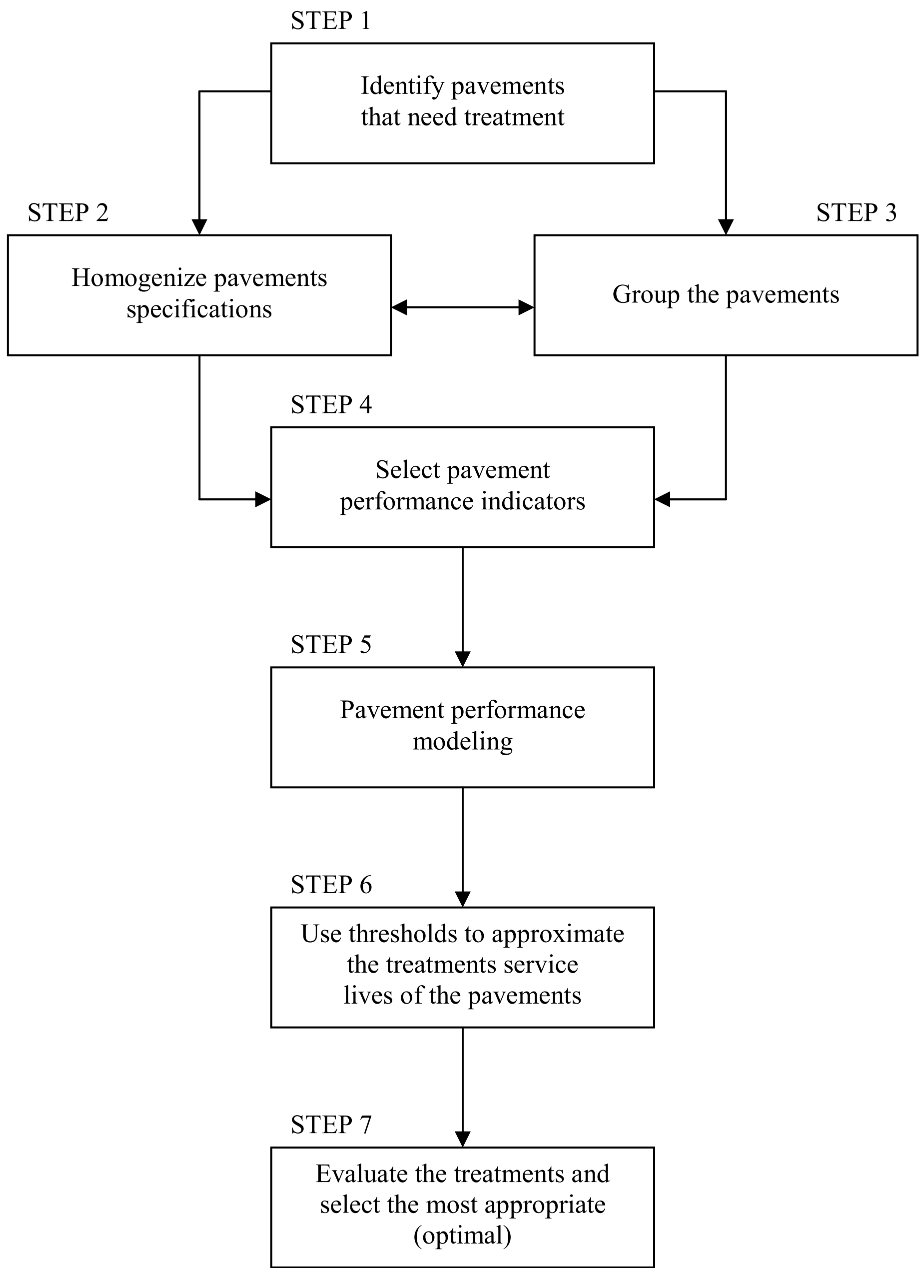


Figure 3.1 General methodological framework

STEP 3. Group pavement segments based on their treatment history and on other homogenous characteristics. In the case of pavement rehabilitation, the pavements are grouped into three major road functional class categories for rural and urban roads; interstates, non-interstates of the National Highway

System, and non-interstates that do not belong in the NHS. For each one of these road functional classes, the pavements are further grouped with respect to the six pavement rehabilitation treatments.

STEP 4. Select the appropriate performance indicators that best specify and represent the pavement's condition. The IRI, PCR and rut depth are identified as the most representative pavement performance indicators that best specify the pavement's condition for the functional treatments (i.e., three-course HMA overlay with or without surface milling, and three-course HMA overlay with crack and seat of PCC pavement); for the structural treatments (i.e., three-course HMA overlay with or without surface milling, three-course HMA overlay with crack and seat of PCC pavement, 3-R and 4-R overlay treatments, and 3-R/4-R pavement replacement treatments) the IRI, PCR, rut depth, and surface deflection are identified as the most representative ones.

STEP 5. Implement the optimal performance modeling approach that critically accounts for potential simultaneous relationships among the performance indicators, and forecast pavement condition in time. For pavement-performance modeling, it is assumed that the pavement condition indicators do not directly influence each other. However, it is observed that if the pavement condition is poor, then some or all performance indicators may also be poor. Hence, the pavement performance in terms of the IRI, PCR, rut depth, and surface deflection for structural treatments, is forecasted as a system of equations, by explicitly accounting for simultaneous relationships that potentially exist among them (at an error-correlation level) using the econometric modeling approach of the Seemingly Unrelated Regression Equations or SURE (Washington et al., 2003).

STEP 6. Utilize performance thresholds onto the pavements' condition deterioration forecasts to estimate the service life for each pavement. The pavement condition can be projected in the future using the pavement performance model. The service life of each treatment for each road section can be approximated by identifying the point in time when the pavement condition first surpasses any of the pavement performance thresholds.

STEP 7. Evaluate each treatment on the basis of their service lives, the current condition of the pavement, the need and priorities of the transportation agency, and select the appropriate treatment (if the treatments are comparable).

3.3. Data: Sources and Description

The data used for pavement performance modeling were collected from the Indiana Department of Transportation pavement condition and pavement management databases and from INDIPAVE (a database consisting of data on pavement condition, weather, pavement structure, traffic, maintenance, and other information at over 10,000 1-mile (1.61 kilometers) pavement sections in the State of Indiana). For purposes of performance modeling, values of pavement performance, traffic loading, weather effects and rehabilitation expenditure were obtained from these databases. Weather information was also collected from the Indiana State Climate Office. The data include information on 12,250 road sections from 1999 to 2007 about:

- the location of each road section (district, county and city information),
- road functional class (rural or urban; interstate, non-interstate NHS, or non-interstate non-NHS),
- drainage condition/class (excessively drained, somewhat excessively drained, well drained, moderately well drained, somewhat poorly drained, poorly drained, or very poorly drained),
- annual average daily traffic (AADT),
- percentage of commercial trucks as part of the AADT,
- rehabilitation contract information (final cost of the contract, year that the contract was let),

- treatment classification (functional or structural treatment),
- treatment type (two-course HMA overlay with or without surface milling, concrete pavement restoration, three-course HMA overlay with or without surface milling, three-course HMA overlay with crack and seat of PCC pavement, 3-R and 4-R overlay treatments, or 3-R/4-R pavement replacement treatments),
- temperature information (averages, minimums, and maximums by month),
- precipitation level (averages, minimums, and maximums by month), and
- IRI, PCR, rut depth and surface deflection average, minimum and maximum values by year.

3.4. Summary Statistics

In order to better describe the collected data and interpret the forthcoming econometric models, summary statistics of selected critical variables for each of the six rehabilitation treatments are computed, and are presented in Tables 3.2 through 3.7, for rural interstates, rural non-interstates of the National Highway System, rural non-interstates that do not belong in the NHS, urban interstates, urban non-interstates of the National Highway System, and urban non-interstates that do not belong in the NHS, respectively. Table 3.1 presents the abbreviations of the variables.

Table 3.1 Abbreviations of selected variables

Variable	Abbreviation
Two-course HMA overlay with or without surface milling	2C HMA
Concrete pavement restoration	C PVM R
Three-course HMA overlay with or without surface milling	3C HMA
Three-course HMA overlay with crack and seat of PCC pavement	3C HMA PCC
3-R and 4-R overlay treatments	3-R & 4-R
3-R/4-R pavement replacement treatments	3-R/4-R
Base (right after treatment) IRI (in/mi)	IRI base
Base (right after treatment) PCR	PCR base
Base (right after treatment) Rut depth (inches)	RUT base
Base (right after treatment) surface deflection (mils)	FWD base
Cumulative (over treatment study period) Daily No. of Trucks (in 1000s)	Trucks
Drainage Class: Excessively or somewhat excessively drained	DR 1
Drainage Class: Excessively, somewhat excessively or well drained	DR 2
Drainage Class: Excessively, somewhat excessively, well, or moderately well drained	DR 3
Drainage Class: Somewhat poorly, poorly, or very poorly drained	DR 4
Drainage Class: poorly or very poorly drained	DR 5
Treatment Contract Final Cost per lane-mile (USD)	COST
Treatment Contract Final Cost per lane-mile (less than 50,000USD)	COST 50K

Table 3.2 Summary statistics of selected variables: rural interstates

	2C HMA	C PVM R	3C HMA	3C HMA PCC	3-R & 4-R	3-R/4-R
	Percentage or Mean (Std. Dev.)	Percentage or Mean (Std. Dev.)	Percentage or Mean (Std. Dev.)	Percentage or Mean (Std. Dev.)	Percentage or Mean (Std. Dev.)	Percentage or Mean (Std. Dev.)
IRI base	56.816 (21.221)	60.376 (25.277)	77.175 (32.282)	44.321 (19.685)	61.302 (23.677)	60.204 (25.556)
PCR base	94.549 (5.018)	93.946 (6.183)	94.638 (5.691)	98.344 (2.635)	94.029 (5.843)	94.747 (5.517)
RUT base	0.086 (0.063)	0.076 (0.049)	0.105 (0.072)	0.086 (0.047)	0.088 (0.058)	0.090 (0.063)
FWD base			5.271 (2.753)	4.677 (2.8)	3.824 (1.883)	3.407 (0.708)
Trucks	18,654.603 (8,100.59)	17,398.09 (7,497.757)	8,113.877 (6,544.322)	14,474.513 (4,583.342)	16,321.632 (7,283.028)	15,519.179 (7,585.503)
DR 1	0.053	0.094	0.114	0.000	0.093	0.040
DR 2	0.214	0.401	0.379	0.170	0.386	0.299
DR 3	0.446	0.575	0.601	0.566	0.550	0.505
DR 4	0.554	0.425	0.400	0.434	0.450	0.495
DR 5	0.224	0.204	0.181	0.189	0.197	0.244
COST	55,402.7 (55,602.3)	290,670 (144,054.16)	170,531.03 (95,508.11)	599,012.235 (214,434.973)	238,928.15 (115,654.703)	370,449.108 (159,382.771)
COST 50K	0.754	0.472	0.567	0.000	0.467	0.306

Table 3.3 Summary statistics of selected variables: rural non-interstates of the NHS

	2C HMA	C PVM R	3C HMA	3C HMA PCC	3-R & 4-R	3-R/4-R
	Percentage or Mean (Std. Dev.)	Percentage or Mean (Std. Dev.)	Percentage or Mean (Std. Dev.)	Percentage or Mean (Std. Dev.)	Percentage or Mean (Std. Dev.)	Percentage or Mean (Std. Dev.)
IRI base	103.821 (42.476)	90.147 (33.501)	82.058 (31.105)	110.075 (52.076)	95.928 (43.277)	76.9 (34.659)
PCR base	93.132 (6.157)	94.735 (4.81)	94.8 (4.757)	92.525 (6.826)	93.167 (5.767)	94.336 (5.868)
RUT base	0.151 (0.091)	0.114 (0.079)	0.11 (0.077)	0.141 (0.095)	0.155 (0.098)	0.122 (0.101)
FWD base			3.883 (1.443)	6.979 (2.774)	4.645 (2.319)	3.962 (1.723)
Trucks	1,438.651 (1,557.725)	955.654 (1,128.744)	2,001.379 (1,914.761)	495.382 (636.469)	1,901.555 (1,793.395)	3,591.965 (3,051.765)
DR 1	0.029	0.038	0.017	0.052	0.060	0.015
DR 2	0.311	0.340	0.277	0.315	0.354	0.384
DR 3	0.582	0.596	0.622	0.606	0.616	0.575
DR 4	0.418	0.404	0.378	0.394	0.384	0.425
DR 5	0.158	0.185	0.178	0.191	0.125	0.178
COST	343,794.115 (180,949.655)	440,682.57 (226,120.905)	171,036.771 (96,109.58)	118,231.229 (116,482.418)	434,751.7 (221,952.041)	589,306.175 (212,033.53)
COST 50K	0.361	0.513	0.316	0.490	0.353	0.132

Table 3.4 Summary statistics of selected variables: rural non-interstates non-NHS

	2C HMA	C PVM R	3C HMA	3C HMA PCC	3-R & 4-R	3-R/4-R
	Percentage or Mean (Std. Dev.)	Percentage or Mean (Std. Dev.)	Percentage or Mean (Std. Dev.)	Percentage or Mean (Std. Dev.)	Percentage or Mean (Std. Dev.)	Percentage or Mean (Std. Dev.)
IRI base	101.366 (49.875)	112.368 (46.729)	90.977 (36.803)	110.335 (46.843)	97.752 (44.55)	101.863 (50.643)
PCR base	92.705 (6.895)	93.881 (5.827)	94.458 (5.114)	93.736 (6.132)	93.994 (6.047)	94.49 (5.63)
RUT base	0.147 (0.106)	0.154 (0.1)	0.115 (0.075)	0.15 (0.097)	0.148 (0.097)	0.142 (0.099)
FWD base			6.769 (3.075)	6.301 (2.866)	5.379 (2.663)	5.092 (3.025)
Trucks	710.662 (662.358)	475.288 (567.119)	587.241 (704.147)	456.506 (555.599)	603.257 (588.154)	643.699 (690.894)
DR 1	0.019	0.022	0.031	0.031	0.110	0.008
DR 2	0.409	0.242	0.331	0.274	0.273	0.270
DR 3	0.636	0.492	0.567	0.557	0.558	0.513
DR 4	0.364	0.508	0.433	0.443	0.442	0.487
DR 5	0.147	0.253	0.193	0.212	0.190	0.243
COST	120,883 (166,735.909)	118,526.551 (100,016.824)	88,057.2 (157,137.66)	114,203.111 (237,645.27)	188,472.9 (341,713.004)	325,104.098 (315,523.128)
COST 50K	0.356	0.665	0.525	0.605	0.573	0.361

Table 3.5 Summary statistics of selected variables: urban interstates

	2C HMA	C PVM R	3C HMA	3C HMA PCC	3-R & 4-R	3-R/4-R
	Percentage or Mean (Std. Dev.)	Percentage or Mean (Std. Dev.)	Percentage or Mean (Std. Dev.)	Percentage or Mean (Std. Dev.)	Percentage or Mean (Std. Dev.)	Percentage or Mean (Std. Dev.)
IRI base	66.976 (28.089)	92.365 (35.118)	72.645 (25.237)	82.46 (32.362)	84.126 (30.881)	69.647 (34.541)
PCR base	94.735 (5.523)	95.236 (5.245)	92.46 (6.725)	93.271 (6.765)	93.463 (5.905)	96.448 (4.603)
RUT base	0.093 (0.07)	0.1 (0.07)	0.097 (0.06)	0.075 (0.046)	0.099 (0.058)	0.077 (0.049)
FWD base			3.827 (1.873)	4.904 (2.632)	6.214 (2.917)	2.731 (0.585)
Trucks	20,715.028 (11,520.641)	4,163.592 (8,263.637)	19,056.468 (9,040.101)	24,712.216 (14,365.78)	12,345.249 (15,536.663)	18,570.981 (7,343.143)
DR 1	0.039	0.023	0.072	0.141	0.095	0.020
DR 2	0.260	0.316	0.462	0.384	0.335	0.322
DR 3	0.361	0.574	0.595	0.498	0.483	0.399
DR 4	0.639	0.426	0.405	0.502	0.517	0.601
DR 5	0.345	0.160	0.196	0.360	0.342	0.193
COST	224,956.307 (851,265.572)	263,373.501 (526,375.108)	699,475.56 (996,210.088)	650,162.644 (896,950.86)	406,790.352 (980,327.824)	657,689.35 (617,015.999)
COST 50K	0.663	0.490	0.471	0.598	0.511	0.007

Table 3.6 Summary statistics of selected variables: urban non-interstates of the NHS

	2C HMA	C PVM R	3C HMA	3C HMA PCC	3-R & 4-R	3-R/4-R
	Percentage or Mean (Std. Dev.)	Percentage or Mean (Std. Dev.)	Percentage or Mean (Std. Dev.)	Percentage or Mean (Std. Dev.)	Percentage or Mean (Std. Dev.)	Percentage or Mean (Std. Dev.)
IRI base	121.972 (52.258)	96.924 (40.292)	99.449 (41.734)	103.975 (46.113)	91.025 (31.927)	97.378 (42.542)
PCR base	93.638 (6.572)	94.654 (4.633)	94.888 (4.905)	91.727 (6.672)	94.013 (5.435)	94.635 (5.197)
RUT base	0.137 (0.091)	0.105 (0.071)	0.105 (0.063)	0.121 (0.077)	0.124 (0.061)	0.101 (0.061)
FWD base			6.31 (3.014)	6.71 (2.677)	6.64 (3.045)	6.47 (3.18)
Trucks	1,660.505 (1,745.726)	1,108.173 (1,484.948)	1,186.71 (1,654.158)	575.499 (793.875)	1,005.962 (1,106.939)	2,555.959 (3,072.023)
DR 1	0.057	0.060	0.205	0.041	0.029	0.058
DR 2	0.511	0.390	0.474	0.302	0.318	0.335
DR 3	0.661	0.602	0.660	0.563	0.498	0.511
DR 4	0.339	0.398	0.340	0.437	0.502	0.489
DR 5	0.118	0.175	0.154	0.176	0.347	0.237
COST	577,261.832 (925,409.169)	231,292.578 (454,320.206)	106,110.88 (198,554.123)	180,217.471 (376,071.049)	157,529.098 (339,017.671)	350,650.07 (686,643.454)
COST 50K	0.329	0.518	0.502	0.336	0.485	0.281

Table 3.7 Summary statistics of selected variables: urban non-interstates non-NHS

	2C HMA	C PVM R	3C HMA	3C HMA PCC	3-R & 4-R	3-R/4-R
	Percentage or Mean (Std. Dev.)	Percentage or Mean (Std. Dev.)	Percentage or Mean (Std. Dev.)	Percentage or Mean (Std. Dev.)	Percentage or Mean (Std. Dev.)	Percentage or Mean (Std. Dev.)
IRI base	97.641 (57.504)	116.711 (75.482)	113.607 (53.506)	117.58 (52.822)	111.753 (44.547)	108.873 (53.2406)
PCR base	94.334 (5.936)	93.797 (6.636)	93.656 (5.929)	93.894 (6.415)	93.922 (6.117)	94.171 (5.185)
RUT base	0.114 (0.086)	0.147 (0.098)	0.121 (0.072)	0.145 (0.101)	0.15 (0.096)	0.14 (0.089)
FWD base			8.225 (3.206)	5.883 (3.29)	4.99 (2.783)	6.674 (2.774)
Trucks	652.868 (717.532)	483.76 (545.124)	1,045.805 (1,213.085)	712.575 (766.325)	586.971 (893.859)	685.656 (777.122)
DR 1	0.355	0.022	0.217	0.077	0.055	0.022
DR 2	0.582	0.286	0.479	0.361	0.320	0.260
DR 3	0.718	0.529	0.637	0.577	0.563	0.480
DR 4	0.282	0.471	0.363	0.423	0.437	0.520
DR 5	0.098	0.197	0.138	0.167	0.200	0.246
COST	153,540.719 (355,802)	172,402.508 (340,383.088)	165,747.888 (350,922.24)	233,055.792 (594,924.365)	128,065.318 (351,108.276)	216,029.514 (490,638.185)
COST 50K	0.603	0.584	0.473	0.515	0.650	0.520

The summary statistics presented above refer to the road sections used in the forthcoming statistical estimation. Note that the pavement condition of rural and urban interstates is in a very good state right after the occurrence of the rehabilitation treatments, as illustrated by the values of the pavement-condition indicators. Non-interstate roads, however, appear to be in a tolerable (but not good condition) after a rehabilitation treatment. It can be generally observed that the pavement condition indicators are consistent. For example, in rural interstates, the mean values for the IRI are low, which indicate that these roads are in good condition. The rut depths and deflection measurements for the same road functional class are also low and the PCR values are almost 100, all of which indicate that the general condition of the pavement is very good. In contrast, the pavement condition indicators for the urban non-interstate roads that do not belong to the National Highway System are generally poor (the IRI, rut depth and surface deflection are all relatively high, and the PCR is relatively low, compared to the corresponding values of the interstates). This reflects the fact that pavement condition indicators are correlated (as one would expect).

Furthermore, note that the cumulative (over the study period) daily number of trucks (in thousands) is relatively higher for interstates, compared to the non-interstate roads.

These preliminary observations may be misleading, because the pavement condition of the road section before the “base” year (when the rehabilitation treatment occurred) is not known. Hence, a comprehensive econometric analysis is required to identify specific relationships among the pavement condition, time, traffic, drainage, and cost.

CHAPTER 4. PAVEMENT PERFORMANCE MODELING

4.1. Introduction

Pavement management systems typically involve five tasks (FHWA, 1999); identification of the pavement performance goals, creation of an inventory of the pavements, recording of measurable condition assessment (e.g., through pavement condition indicators) in relation to goals, performance modeling (e.g., forecasts of pavement deterioration), and analysis of alternatives (what is the service life of each treatment?).

The present chapter deals with the first four tasks of pavement management systems, with a particular focus on the pavement performance modeling of the six rehabilitation treatments for the six road functional classes. As such, pavement-performance modeling can be defined as a scientific/mathematical technique of describing the pavement-system functions from high to low levels of detail, so that they can be simulated over time. The goal is to forecast how the condition of the pavement deteriorates over time. Once pavement performance is predicted, strategies to best preserve the pavement can be identified, and cost effective solutions can then be implemented.

4.2. Methodology

The first step in modeling pavement performance is to identify the performance goals. Developing the performance goals is a planning process that identifies a set of definite goals. These must be specific, measurable, attainable, results-oriented, and time-framed. The next step is to draw up an inventory of the pavements that need to be preserved, and measure their condition. Having historical condition information, a forecast of pavement performance can be undertaken. As a final step, different treatment alternatives need to be evaluated, and the optimal (according to pre-specified criteria) can be selected (if the treatments are comparable).

Pavement systems typically operate in complex and dynamic environments. This makes it very difficult to streamline and optimize the support necessary to ensure that the required performance is achieved (with minimum life cycle cost, safety, environmental and other impacts). The easiest way to deal with such complexities is to simply budget for extreme reserve (plan for the worst). With this extreme assumption, traditional analytic, non-time dependent, modeling approaches can be applied. However, this approach is potentially expensive in terms of materials, equipment usage, aging of the infrastructure, environmental conditions (e.g., weather changes due to global warming), preservation techniques and their effectiveness. The uncertainty originating from the dynamic changes of these factors needs to be efficiently and accurately dealt with.

The framework for effective modeling of pavement performance can be generalized into the following steps (Figure 4.1):

STEP 1. Identify pavement performance indicators (PI) that best describe the pavement's condition and corresponding treatment, and influential factors that may affect it.

STEP 2. Investigate if these pavement-performance indicators are correlated with each other, or if there is a mechanistic process that can explain potential simultaneous relationships.

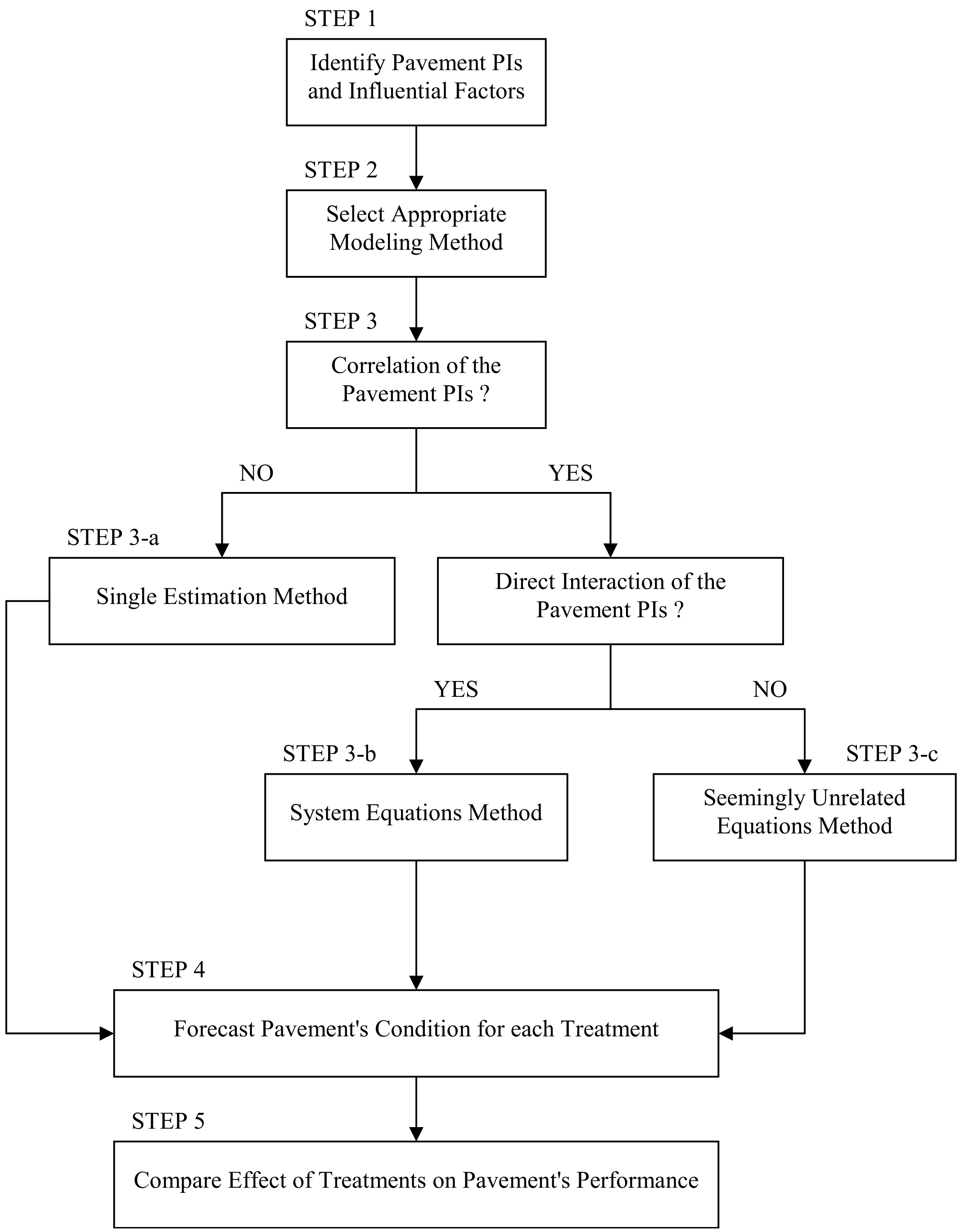


Figure 4.1 Pavement performance modeling with performance indicators (PI)

STEP 3. Select the appropriate method to model pavement performance. For example, if the performance indicator is measured with continuous values that can take decimals, then utilize some linear or logarithmic regression technique (adjusting for irregularities in the data, such as censoring, truncation, etc.). If the indicator is categorized into ranks (e.g., good, fair, and poor), then utilize discrete choice modeling techniques (again adjusting for irregularities in the data, such as unobserved heterogeneity, nests within the categories, etc.). If the performance indicator consists of count data, then use count data modeling techniques (e.g., Poisson, negative binomial, zero-inflated probability models) and adjust the model for unobserved heterogeneity across observations (using random parameters) or for censoring and truncation.

STEP 3-a. If pavement performance indicators are not correlated with each other (there is no direct interaction), model each performance indicator separately, using single-equation estimation methods.

STEP 3-b. If pavement performance indicators are correlated and there is a theory behind their simultaneous relationships (hence there is a direct interaction among the indicators), model them as a system of equations (using system-equation estimation methods) where each performance indicator corresponds to an equation, and the other performance indicators are considered to be influential factors of this indicator. In words, each pavement performance indicator serves both as a dependent variable in one equation, and as an independent variable for the other indicators in the other equations.

STEP 3-c. If pavement performance indicators are somehow correlated so that they can be considered to be a group (they share some unobserved characteristics), but do not have the direct interaction that the simultaneous equations have (there is no theory to support simultaneous relationships), model the performance indicators as a system of seemingly unrelated equations, accounting for contemporaneous (cross-equation) correlation of the error terms.

STEP 4. Use the resulting equations (single equation for each pavement performance indicator, or system of equations) to forecast the pavement's condition in time for each treatment.

STEP 5. Counterpoise pavement performance corresponding to each treatment (if the treatments and/or attributes are comparable), and compare the effect that each treatment has on pavement performance over time.

With respect to the pavement rehabilitation case (PRC), the steps to model the pavement performance would be as follows.

STEP PRC-1. The performance indicators that best describe the pavement condition for the six rehabilitation treatments are assumed to be the international roughness index (IRI) measured in inches per mile, the rut depth (RUT) measured in inches, the pavement condition rating (PCR) measured on a scale from 0 to 100, and for the structural treatments the surface deflection (FWD) measured in mils (one mil is 10^{-3} inches). These are typically used in literature for pavement performance modeling. Influential factors of these pavement-condition indicators are time (in the form of the pavement condition of the preceding years or of the base year (the year that last rehabilitation occurred)), traffic loads (the effect of trucks), weather conditions, soil type beneath the pavement's surface, drainage condition, and contract cost of the most recent implemented rehabilitation treatment.

STEP PRC-2. Table 4.1 presents the correlation coefficients for the four pavement condition indicators, and Figures 4.2 through 4.7 illustrate their relationships. Note that these values refer to the pavement condition right after rehabilitation. From the correlation coefficients (signs and magnitudes) and the graphical representation of the relationship among the pavement condition indicators, there is a speculative positive relationship between IRI, RUT and

FWD, and a negative relationship among PCR and IRI, rut depth and FWD. This means that smooth road sections (with low IRI) tend to have low RUT and FWD, and high PCR; road sections with low PCR tend to have high IRI, RUT and FWD, and so on. Although there is a relationship among the indicators, there is no scientific evidence that can support the theory that there are strong underlying simultaneous relationships.

Table 4.1 Correlation coefficients for the pavement condition indicators (right after rehabilitation has occurred)

	IRI	PCR	RUT	FWD
IRI	1.000	-0.565	0.620	0.511
PCR	-0.565	1.000	-0.675	-0.476
RUT	0.620	-0.675	1.000	0.440
FWD	0.511	-0.476	0.440	1.000

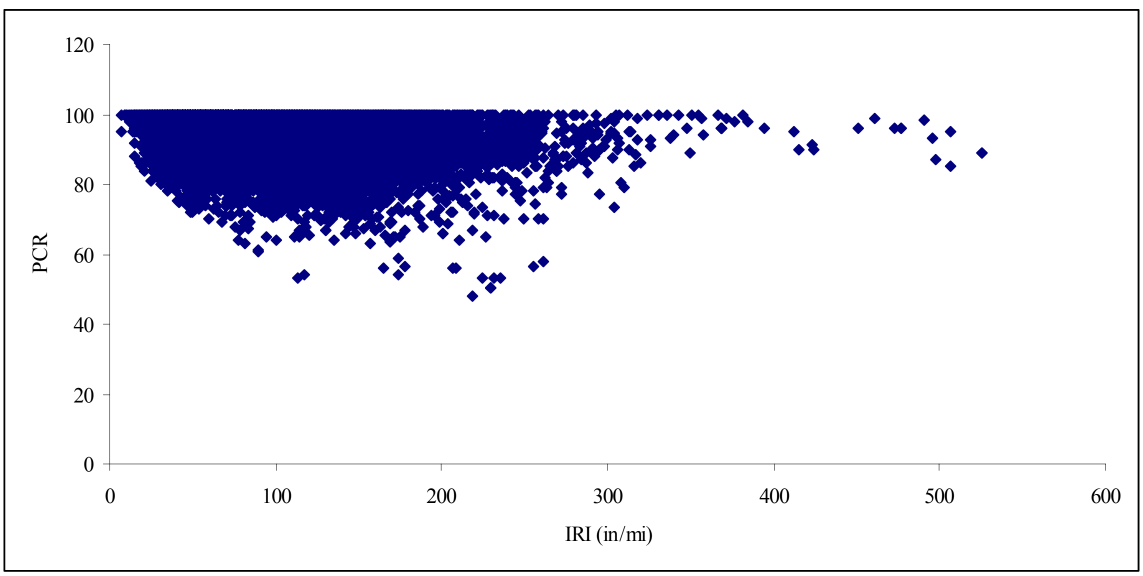


Figure 4.2 Relationship between IRI and PCR

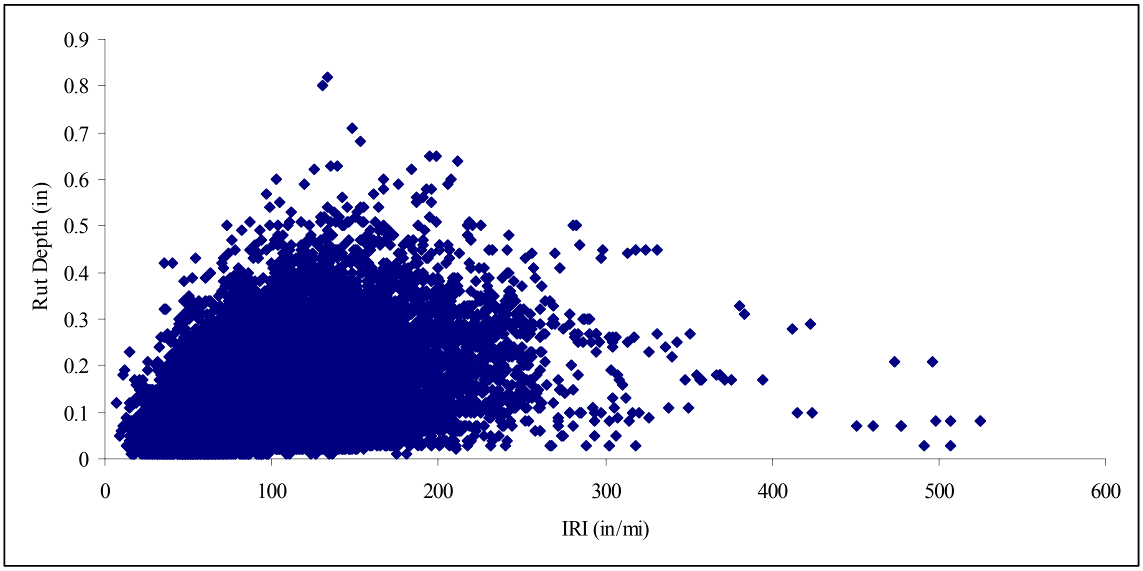


Figure 4.3 Relationship between IRI and rut depth

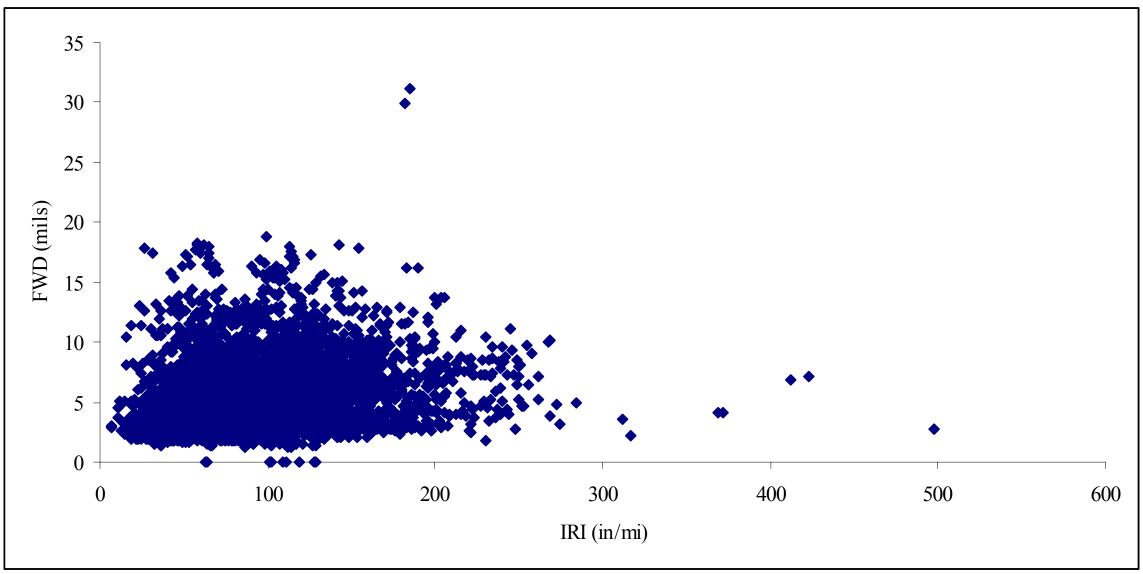


Figure 4.4 Relationship between IRI and FWD

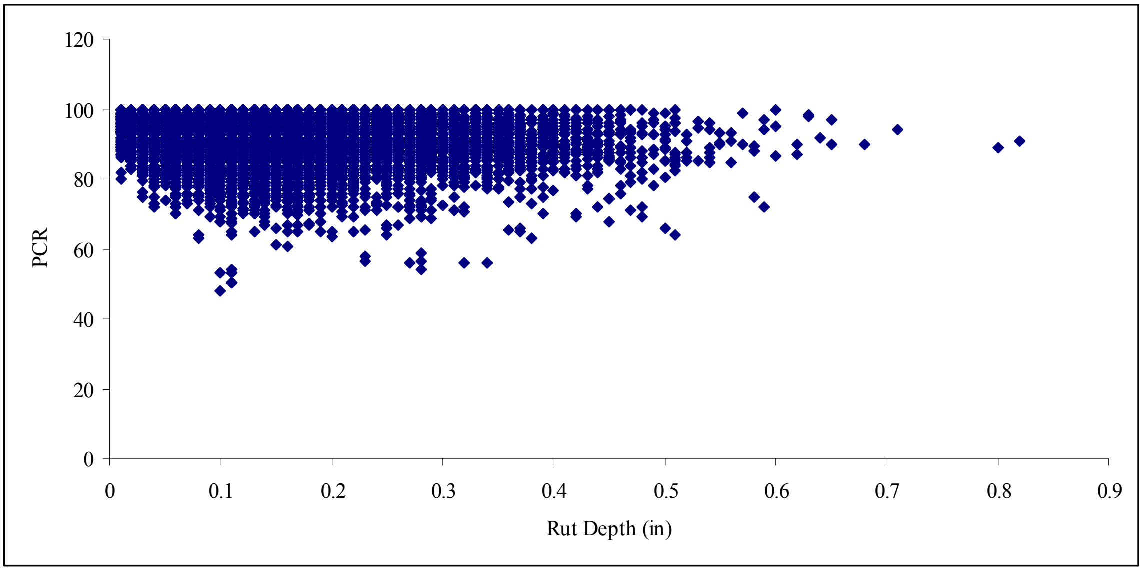


Figure 4.5 Relationship between PCR and rut depth

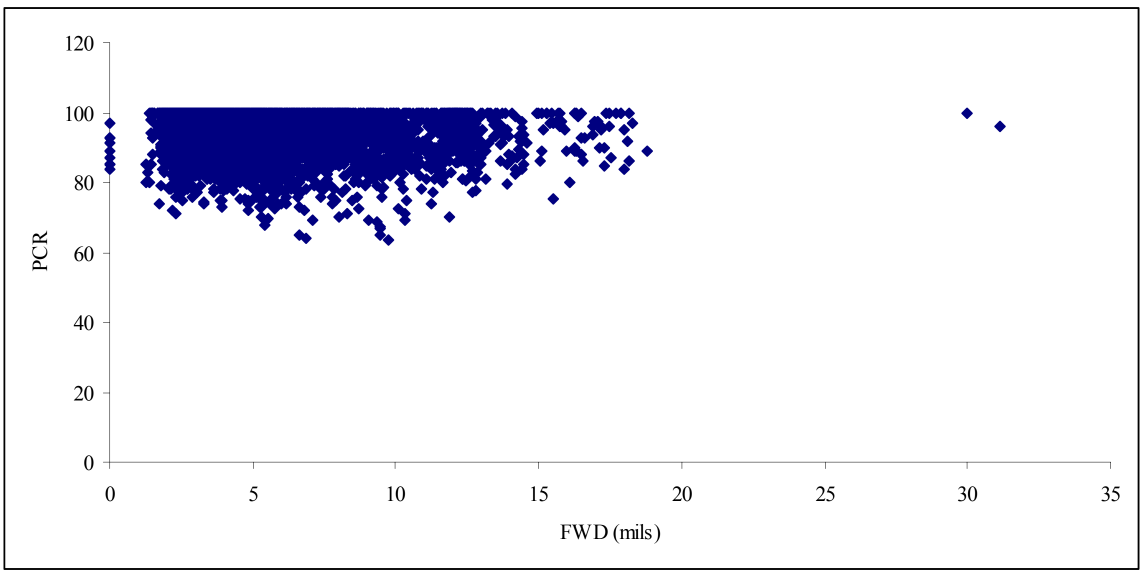


Figure 4.6 Relationship between PCR and FWD

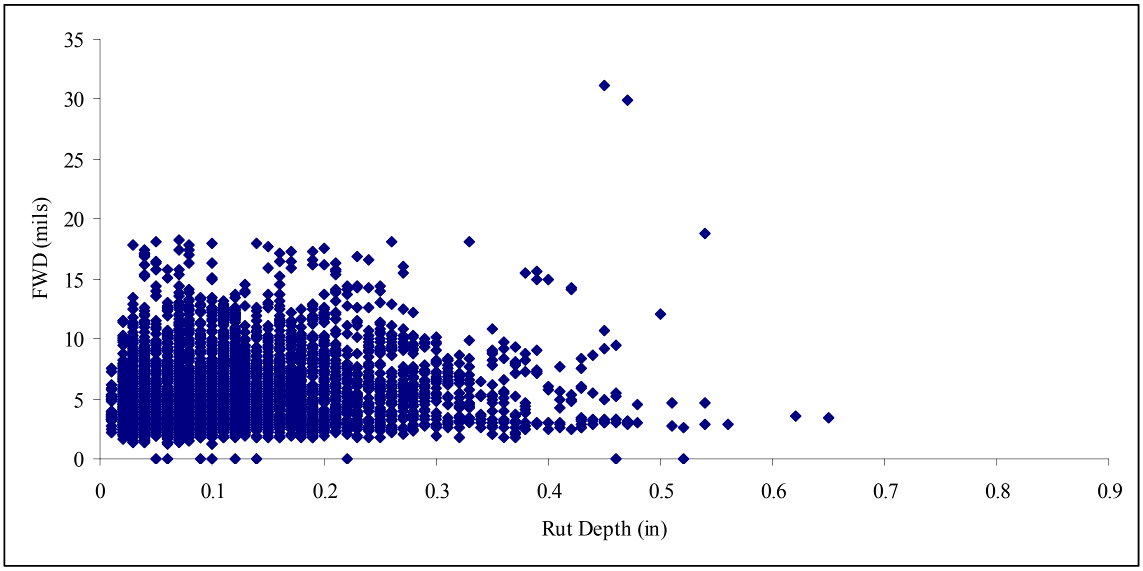
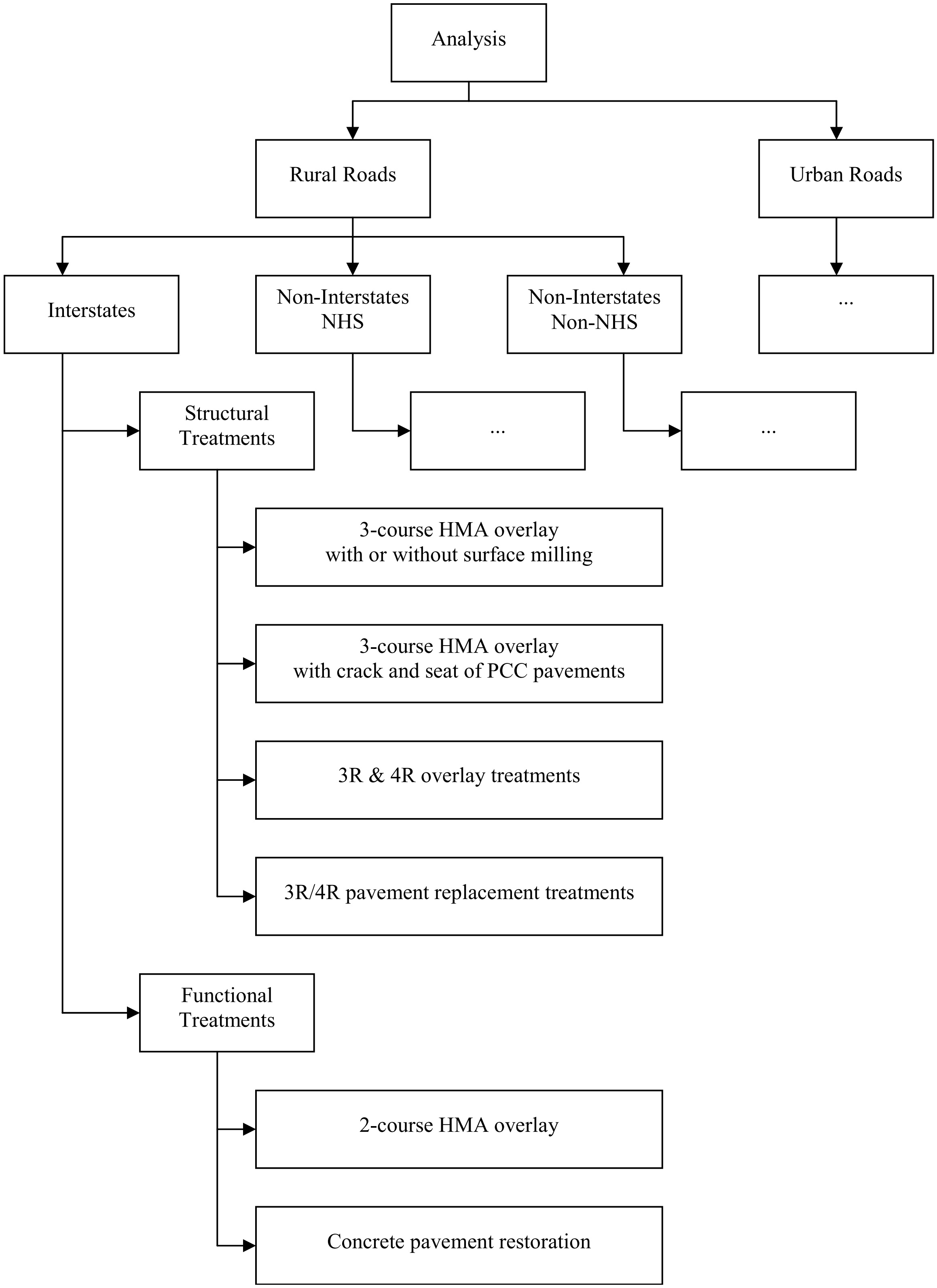


Figure 4.7 Relationship between rut depth and FWD

STEP PRC-3. All four dependent variables (i.e., IRI, PCR, RUT, and FWD) are continuous. Hence, econometric modeling techniques for continuous data are the most appropriate. Even though the pavement condition indicators do not have direct interactions as simultaneous equations have (there is no theory to support simultaneous relationships), they are correlated. Therefore, it is assumed that they can be considered to be a group (they share some unobserved characteristics). Hence, the performance indicators can be modeled as a system of seemingly unrelated regression equations (SURE), accounting for contemporaneous (cross-equation) correlation of the error terms.

STEP PRC-4. Using the system of the four (one for each pavement condition indicator) seemingly unrelated regression equations, 36 SURE models are developed, one for each pavement rehabilitation treatment for each road functional class (Figure 4.8). The estimated models can by utilized to forecast the pavement condition (the next section presents paradigms of the models applicability).



Note that 3R refers to resurfacing, restoration and rehabilitation, and 4R to 3R plus reconstruction.

Figure 4.8 Description of the analysis segmentation

STEP PRC-5. Using the forecasts of the pavement condition for each rehabilitation treatment, the effectiveness of the treatments can be assessed, in terms of the rate that the pavement condition deteriorates over time. Because each rehabilitation type treats different symptoms of the pavement, the treatments are not directly comparable.

4.2.1. Overview of the Econometric Modeling Approach

The dependent variables are the condition indicators that are associated with the determination of pavement performance, and are analyzed simultaneously using econometric techniques. Although it can be assumed that pavements in poor condition have relatively poor condition indicators, it is difficult to assess if the indicators should be treated as endogenous variables. Endogenous variables are those whose value is determined as part of a system of equations (Washington et al., 2003). If these variables are assumed to be endogenous and are modeled using ordinary least squares regression, the estimated parameters will be biased because there will be correlation between the random error terms and the random variables. This is due to the presence of the other random variables as explanatory variables in the model[27]. One of the assumptions of the single-equation ordinary least squares regression is that the independent variables are fixed and do not vary with the dependent variable (Washington et al., 2003). However, because the pavement condition indicators may be assumed to be endogenous, they vary (just like the error terms) and, therefore, all of them have to be modeled simultaneously using system equation methods.

System equation methods are used when several dependent variables are modeled simultaneously. Each dependent variable is modeled using a separate regression equation. Hence, the number of regression equations in the system is equal to the number of dependent variables that are modeled simultaneously. Although the regression model for each dependent variable is separate, the parameters of the

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[27] This is because the error term and one of the independent variables in the model are random in nature.

regression models are estimated simultaneously to account for the intertwined nature of the dependent variables. Mathematically, the system of the regression models can be represented as follows:

$$\begin{aligned} Y_1 &= f(x) + \varepsilon_1 \\ Y_2 &= f(x') + \varepsilon_2 \\ Y_3 &= f(x'') + \varepsilon_3 \\ &\ldots \end{aligned}, \qquad (1)$$

where, Y_1, Y_2, Y_3, ... represent the pavement's condition indicators, x, x', x'', ... represent the set of explanatory variables that are used to determine each pavement's condition indicator, and the terms ε_1, ε_2, ε_3, ... are random errors associated with the respective models of the pavement condition indicators. In addition to the random nature of the dependent variables, the random error term also accounts for unobserved characteristics. The error terms will be correlated if they refer to the same set of unobserved characteristics. The extent of correlation depends on the number of unobserved characteristics that are shared between the equations.

Herein, there are four variables (IRI, PCR, rut depth, and surface deflection for the structural treatments) that are modeled simultaneously. Mathematically, the system of the regression models can be represented as follows:

$$\begin{aligned} IRI &= f(x) + \varepsilon_1 \\ PCR &= f(x') + \varepsilon_2 \\ RUT &= f(x'') + \varepsilon_3 \\ FWD &= f(x''') + \varepsilon_4 \end{aligned}, \qquad (2)$$

where, *IRI* is the international roughness index, *PCR* the pavement condition rating, *RUT* the rut depth, *FWD* the surface deflection, x, x', x'', and x''' represent the set of explanatory variables that are used to determine the *IRI*, *PCR*, *RUT*, and *FWD*, respectively, and the terms ε_1, ε_2, ε_3, and ε_4 are random errors associated with the respective models of the pavement condition indicators.

The choice of the system equation method depends on the nature of relationship between the dependent variables. If Y_1, Y_2, Y_3, ... are endogenous, that is, Y_2 belongs to the set of influential factors (X) that are used to explain the variation in Y_1, Y_1 belongs to the set of influential factors (X') that are used to explain the variation in Y_2, an so on, then the two-stage least squares (2SLS) method is used to estimate the parameters of the two equations simultaneously. On the other hand, if the dependent variables share the same unobserved influential factors and the random error terms are correlated, parameters are obtained using the seemingly unrelated regression equations (SURE) technique. It is important to note that the two stage least squares method does not account for possible correlation among the error terms. Also, the SURE method does not assume that the dependent variables are endogenous. Therefore, if the dependent variables are endogenous and the error terms are correlated, the three stage least squares (3SLS) method is used to estimate the parameters of the equations simultaneously. Table 4.2 presents a decision rule for the selection of the appropriate system equation method depending upon the nature of the relationship among the dependent variables.

Table 4.2 Decision rule for selection of the appropriate system equations method

Estimation Method	Simultaneous Modeling of Endogenous Variables as Dependent Variables	Cross-Equation Error Correlation
OLS	No	No
2SLS	Yes	No
SURE	No	Yes
3SLS	Yes	Yes

The objective in two-stage least square is to model the system of equations represented by Equation 2 simultaneously (Washington et al., 2003):

$$\begin{aligned}
&Y_1 = f(x, Y_2, Y_3, ...) + \varepsilon_1 \\
&Y_2 = f(x', Y_1, Y_3, ...) + \varepsilon_2 \\
&Y_3 = f(x'', Y_2, Y_3, ...) + \varepsilon_3 \\
&...
\end{aligned} \quad . \tag{3}$$

This system equation econometric technique accounts for the simultaneous equation bias introduced from the presence of endogenous dependent variables. No assumption is made about the distribution of the equation error terms. The least squares approach is used for the estimation of the simultaneous equations. In the first stage, a set of explanatory factors (referred to as instrumental variables) are used as regressors to obtain the projected value of the dependent variable. In Stage 2, the predicted value of the dependent endogenous variable from Stage 1 is used to replace the endogenous variable on the right hand side. As a result, consistent least square parameter estimates can be obtained after Stage 2. The instrumental variables approach is used to resolve the endogenous dependent variables problem. The purpose of Stage 1 is to create new dependent or endogenous variables to substitute the original ones. Hence, the problem of a random independent variable is resolved and the independent variables are no more related to the error terms.

Seemingly unrelated Regression Equations (SURE) method is used to analyze a number of regression functions with correlated error terms. Such correlation between the error terms is referred to as contemporaneous correlation (Washington et al., 2003). Although the equations might seem unrelated, they are indeed related through the correlation in the error terms. The SURE method uses the correlations between the error terms of the system of equations to improve upon the parameter estimates. In SURE analysis, the Ordinary Least Squares (OLS) regression of dependent variable against the exogenous variables is first carried out to obtain the parameter estimates and residuals. The obtained residuals are used to determine the cross equation correlation matrix. In the next step, the error correlation matrix is used to improve upon the parameter estimates using Generalized Least Squares (GLS). The inclusion of this variance-covariance matrix, in the estimation of the beta coefficients (using the GLS method) improves the efficiency (minimum variance assumption) of the estimates. The efficiency of the estimates is significantly improved especially when the disturbances (i.e., the error terms) are highly correlated, but the independent variables are not.

The SURE method is also referred to as Joint Generalized Least Squares Estimation (JGLS) or Zellner Estimation (Washington et al., 2003). It is a technique for analyzing a system of multiple equations with cross-equation parameter restrictions and correlated error terms. The SURE method generalizes the OLS method and hence produces improved parameter estimates by taking into account the correlation between the errors terms in each equation. The method assumes that there are no endogenous variables present and that the number of observations is the same for all the equations.

Three-stage least squares (3SLS) accounts for both simultaneous equation bias and cross-equation contemporaneous correlation of the errors, and makes no assumption about the distribution of the equation error terms. Three-stage least squares is a combination of 2SLS and SURE. The parameter estimates are consistent and asymptotically normal, and typically more efficient than single equation estimates.

According to Washington et al. (2003), in Stage 1, estimates of the endogenous dependent variables are obtained using instrumental variables. In Stage 2, the residuals are estimated for each equation and the correlation between the error terms is calculated using these residuals. In this step, the endogenous variables are replaced by their predicted values (from Stage 1) on the right hand side of the equations. Until this step, the process used in 3SLS is exactly the same as that used in 2SLS. The error term correlation matrix is calculated from the residuals obtained at this stage. These residuals are referred to as 2SLS residuals. In Stage 3, error term correlations are used to improve upon the parameter estimates from Stage 2. The parameter estimates obtained from

3SLS are consistent and asymptotically normal, and even asymptotically more efficient than the single equation estimates.

An important distinction is that the cross equation error correlation matrix is computed differently in 3SLS and in SURE. In 3SLS, the 2SLS residuals are used to compute the error correlation matrix, whereas in SURE the OLS residuals are used. In 3SLS, the 2SLS residuals are computed after the endogenous variables problem is resolved. In SURE, there is no endogenous variable problem and therefore the OLS residuals are used to compute the error correlation matrix.

With respect to this study, and for the reasons discussed above, the seemingly unrelated regression equation approach is used to model the pavement condition indicators as a system of equations. As such, the system of the seemingly unrelated regression equations model can be mathematically represented as follows:

$$\begin{aligned} PI_1 &= \beta_1 Z_1 + \alpha_1 X + \varepsilon_1 \\ PI_2 &= \beta_2 Z_2 + \alpha_2 X + \varepsilon_2 \\ PI_3 &= \beta_3 Z_3 + \alpha_3 X + \varepsilon_3 \\ PI_4 &= \beta_4 Z_4 + \alpha_4 X + \varepsilon_4 \end{aligned}, \qquad (4)$$

where, PI_1, PI_2, PI_3, and PI_4 represent the four pavement condition indicators *IRI*, *PCR*, *RUT*, and *FWD*[28], respectively, Z_1, Z_2, Z_3, and Z_4 are road section and pavement condition characteristics, X is a vector of influential factors affecting the pavement condition, the β and α are vectors of estimable parameters, and the ε the disturbance terms.[29] Statistically, there is no direct interaction among the four pavement condition indicators. That is, *IRI* does not directly determine *PCR*, *RUT*, and *FWD*, *PCR* does not directly determine *IRI*, *RUT*, and *FWD*, and so on. However, this method (i.e., SURE)

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[28] Note that the surface deflection (FWD) is a pavement condition with respect to structural rehabilitation treatments only.

[29] Note that transformations (logarithmic, exponential, power forms, and so on) of the dependent and independent variables were tested while developing the models, but the linear relationships provided the best overall fit.

accounts for contemporaneous (cross-equation) correlation of error terms, and provides unbiased, consistent, and efficient parameter estimates (Washington et al., 2003).

The statistical significance of individual parameters in the SURE models is approximated using the test statistic *t*-stat. The R-square (R^2) statistic is used to evaluate the overall significance of the model. To account for the estimation of potentially insignificant parameters, a corrected or adjusted R-square is estimated as (Washington et al., 2003):

$$Adjusted\ R^2 = \overline{R}^2 = 1 - R^2 \cdot \frac{N-1}{N-K}, \tag{5}$$

where, N the number of observations, and K = the number of parameters estimated in the model. If $\overline{R}^2$ decreases when additional variables are introduced in the model, it can be concluded that the additional variables do not appear to add sufficient explanatory power to the model to compensate for the degrees of freedom utilized by the fuller specification.

4.2.2. Descriptive Statistics

Table 4.3 presents the list of abbreviations used to represent the variables described in Figures 4.9 through 4.32 and in Tables 4.4 through 4.39. The Figures present mean values of each pavement condition indicator for the base year (staring with year 1 - the year right after the most recent rehabilitation), and three consecutive years (years 2, 3, and 4, respectively) after the base year (provided that no rehabilitation has occurred during the four year period) with respect to all the treatments and road functional classes. Note that the six most commonly implemented rehabilitation treatments in the State of Indiana (according to the Indiana Design Manual, Chapter 52; INDOT, 2008) have been selected for the case study.

Table 4.3 Abbreviations of variables related to the pavement condition

Variable	Abbreviation
Two-course HMA overlay with or without surface milling	2C HMA
Concrete pavement restoration	C PVM R
Three-course HMA overlay with or without surface milling	3C HMA
Three-course HMA overlay with crack and seat of PCC pavement	3C HMA PCC
3-R and 4-R overlay treatments	3-R & 4-R
3-R/4-R pavement replacement treatments	3-R/4-R
Base (right after treatment) IRI (in/mi)	IRI base
Base (right after treatment) PCR	PCR base
Base (right after treatment) Rut depth (inches)	RUT base
Base (right after treatment) surface deflection (mils)	FWD base
IRI measured one year after the base year (in/mi)	IRI base+1
PCR measured one year after the base year	PCR base+1
Rut depth measured one year after the base year (inches)	RUT base+1
FWD measured one year after the base year (mils)	FWD base+1
IRI measured two years after the base year (in/mi)	IRI base+2
PCR measured two years after the base year	PCR base+2
RUT measured two years after the base year (inches)	RUT base+2
FWD measured two years after the base year (mils)	FWD base+2
IRI measured three years after the base year (in/mi)	IRI base+3
PCR measured three years after the base year	PCR base+3
RUT measured three years after the base year (inches)	RUT base+3
FWD measured three years after the base year (mils)	FWD base+3

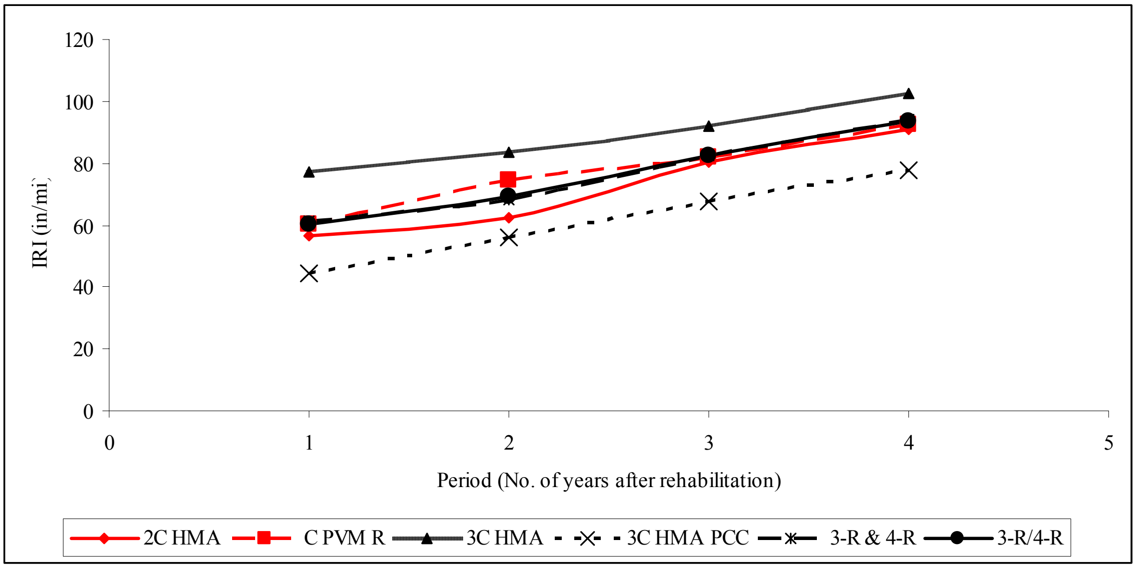

Figure 4.9 Mean IRI in rural interstates for the base year (year 1) and the three consecutive years (years 2, 3, and 4) for each rehabilitation treatment

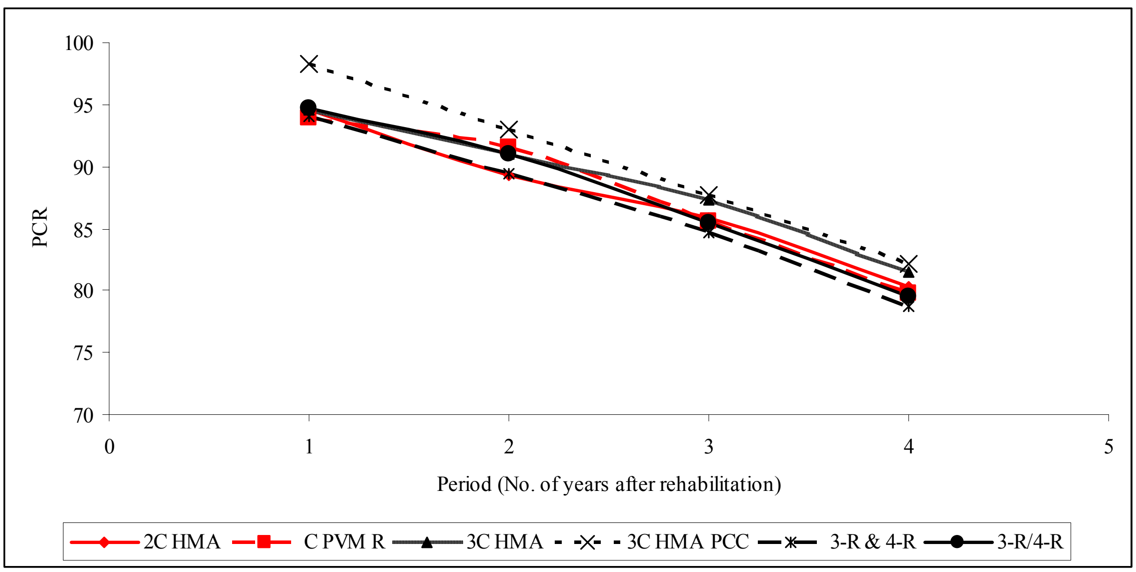

Figure 4.10 Mean PCR in rural interstates for the base year (year 1) and the three consecutive years (years 2, 3, and 4) for each rehabilitation treatment

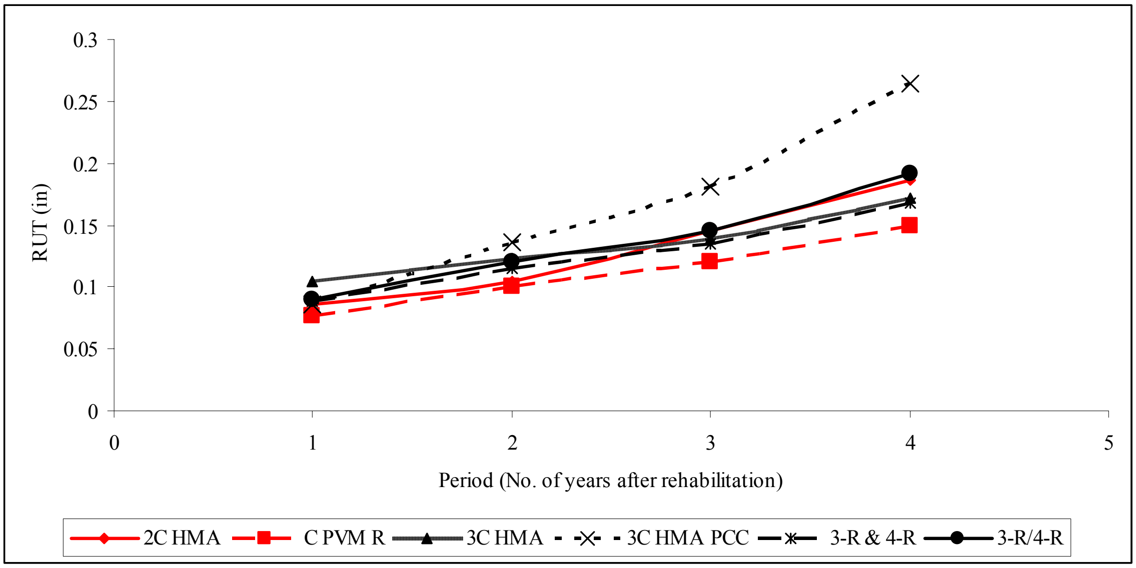

Figure 4.11 Mean rut depth in rural interstates for the base year (year 1) and the three consecutive years (years 2, 3, and 4) for each rehabilitation treatment

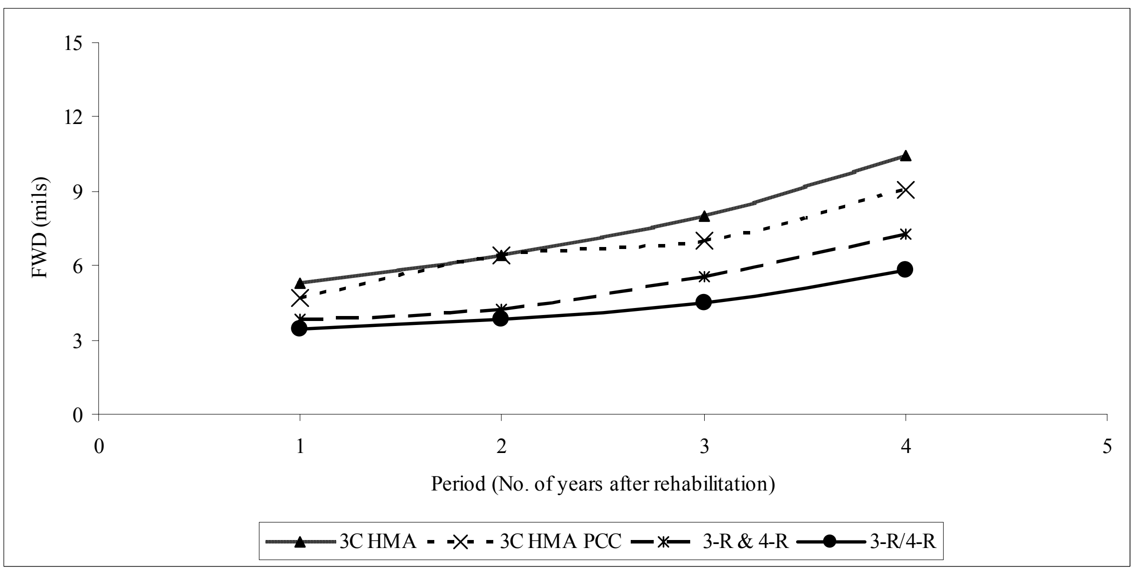

Figure 4.12 Mean deflection in rural interstates for the base year (year 1) and the three consecutive years (years 2, 3, and 4) for each rehabilitation treatment

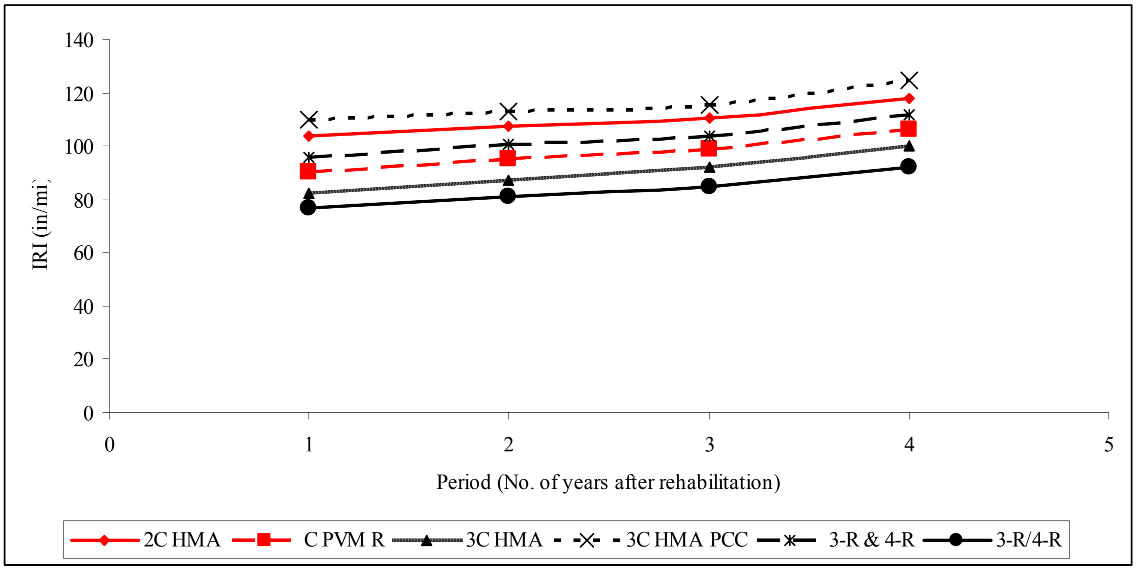

Figure 4.13 Mean IRI in rural non-interstates of the NHS for the base year (year 1) and the three consecutive years (years 2, 3, and 4) for each rehabilitation treatment

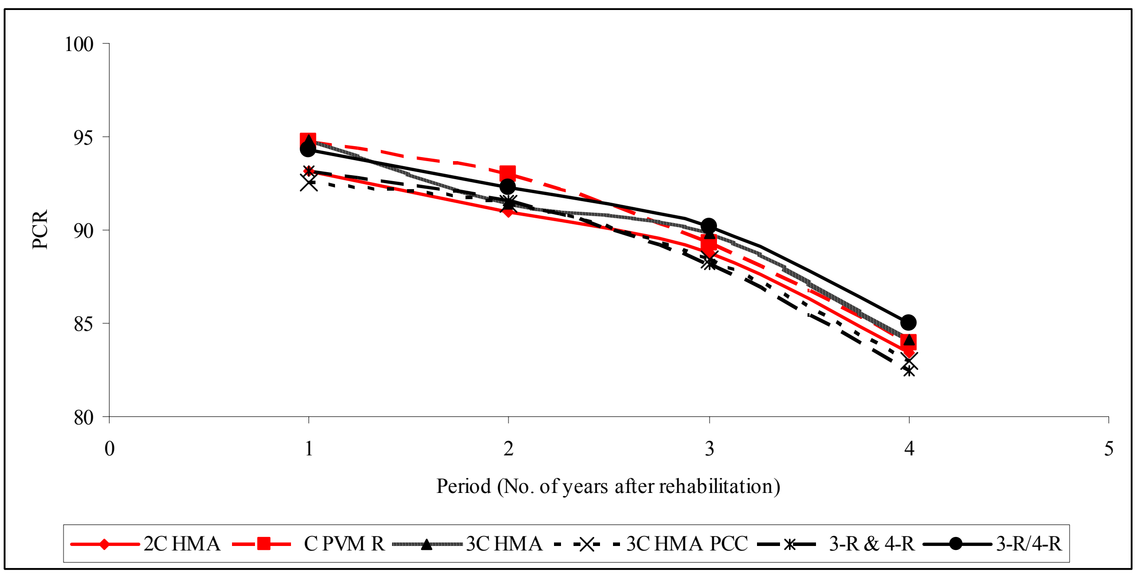

Figure 4.14 Mean PCR in rural non-interstates of the NHS for the base year (year 1) and the three consecutive years (years 2, 3, and 4) for each rehabilitation treatment

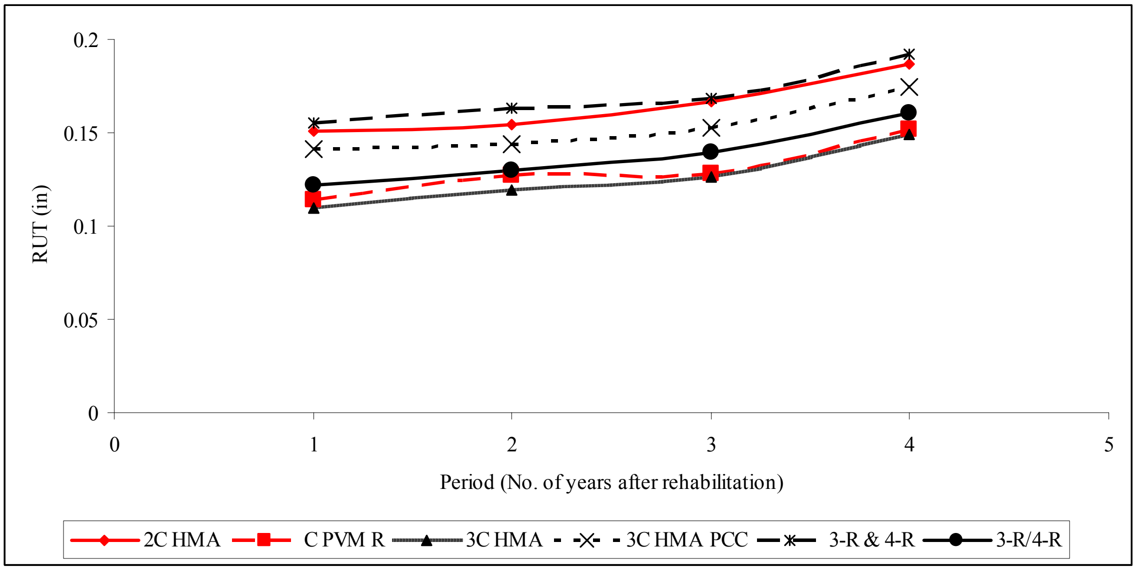

Figure 4.15 Mean rut depth in rural non-interstates of the NHS for the base year (year 1) and the three consecutive years (years 2, 3, and 4) for each rehabilitation treatment

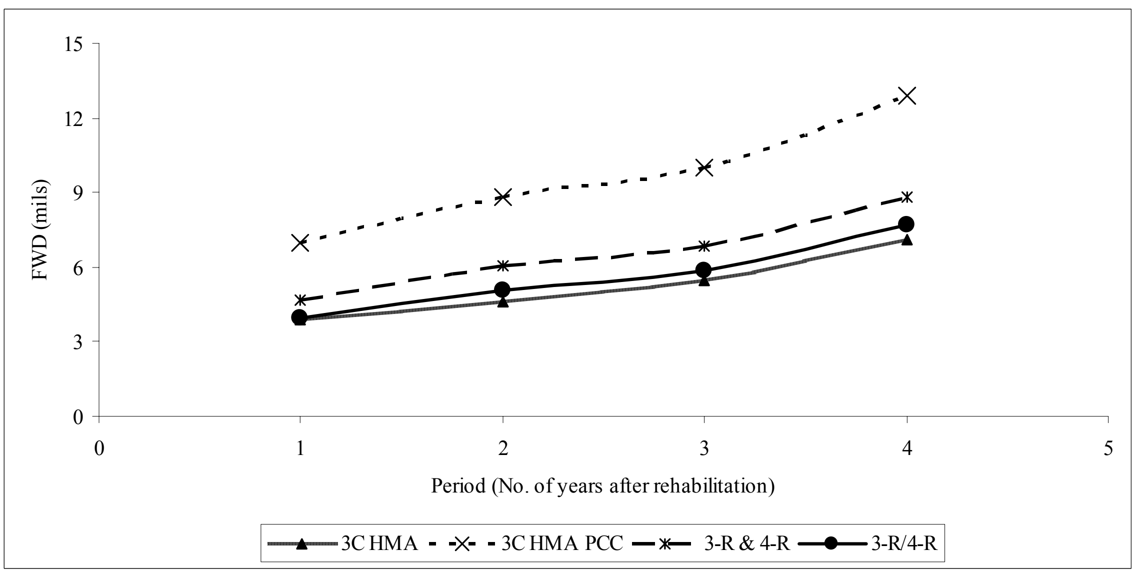

Figure 4.16 Mean deflection in rural non-interstates of the NHS for the base year (year 1) and the three consecutive years (years 2, 3, and 4) for each rehabilitation treatment

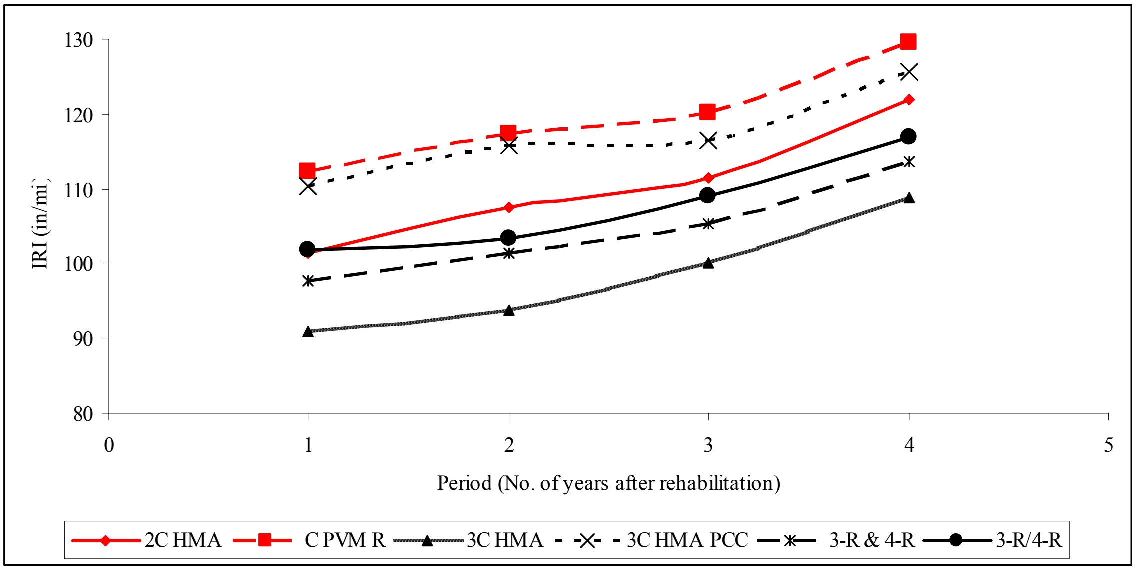

Figure 4.17 Mean IRI in rural non-interstates non-NHS for the base year (year 1) and the three consecutive years (years 2, 3, and 4) for each rehabilitation treatment

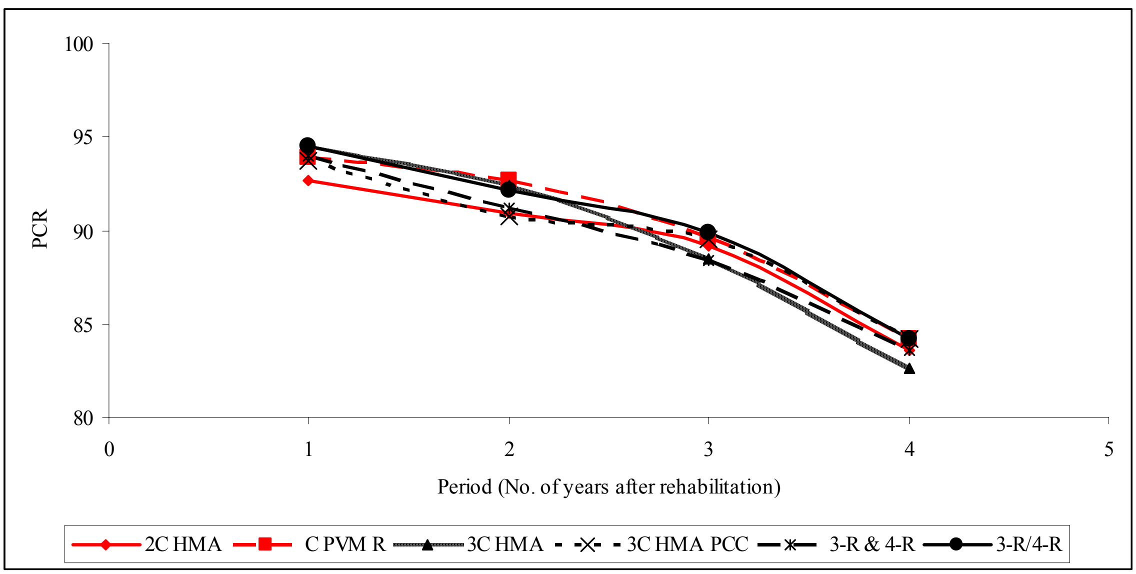

Figure 4.18 Mean PCR in rural non-interstates non-NHS for the base year (year 1) and the three consecutive years (years 2, 3, and 4) for each rehabilitation treatment

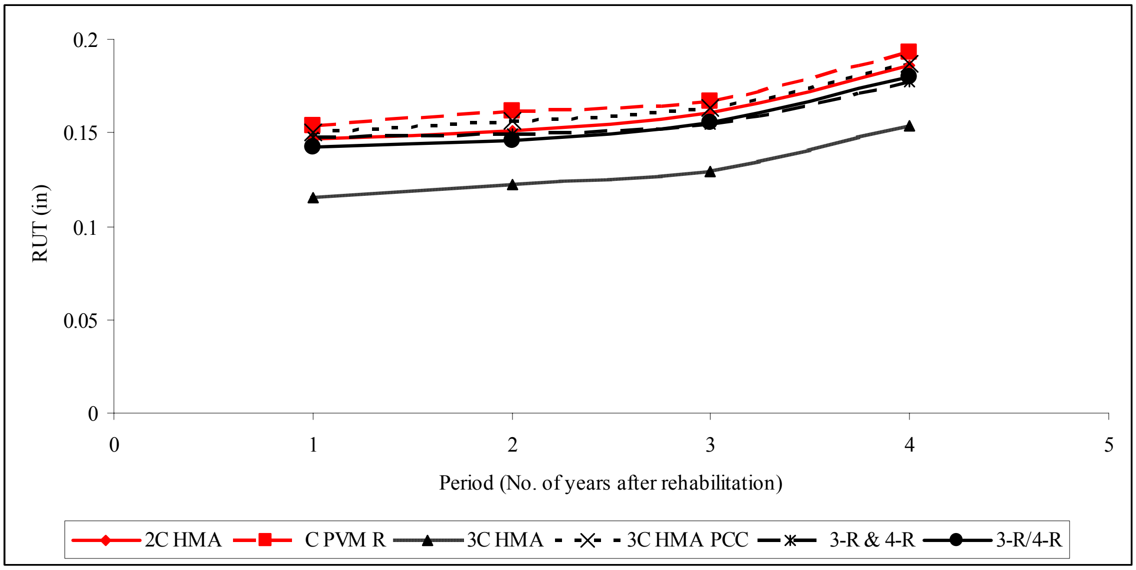

Figure 4.19 Mean rut depth in rural non-interstates non-NHS for the base year (year 1) and the three consecutive years (years 2, 3, and 4) for each rehabilitation treatment

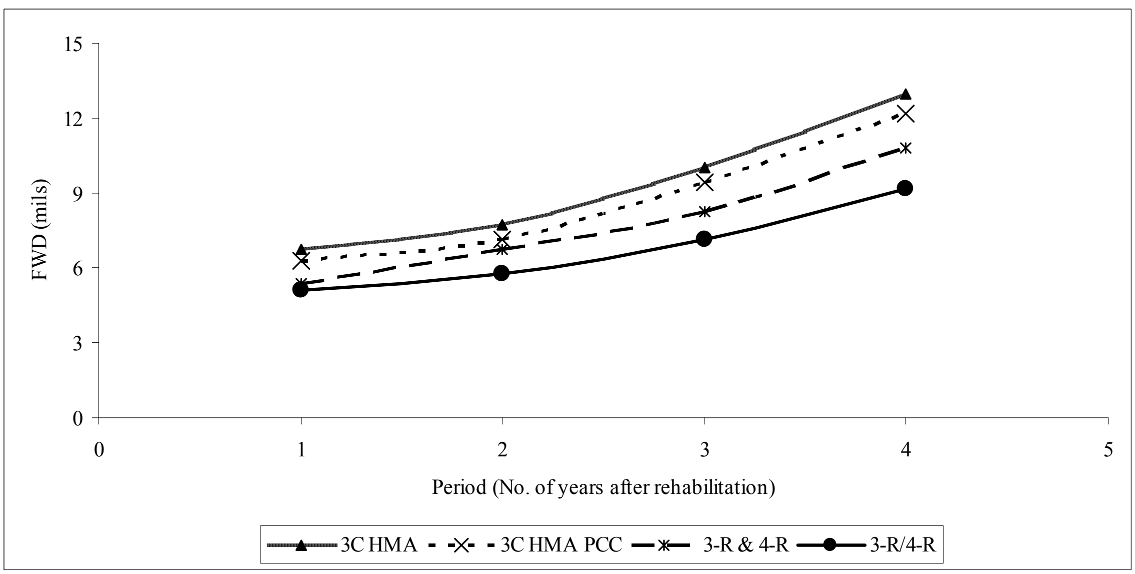

Figure 4.20 Mean deflection in rural non-interstates non-NHS for the base year (year 1) and the three consecutive years (years 2, 3, and 4) for each rehabilitation treatment

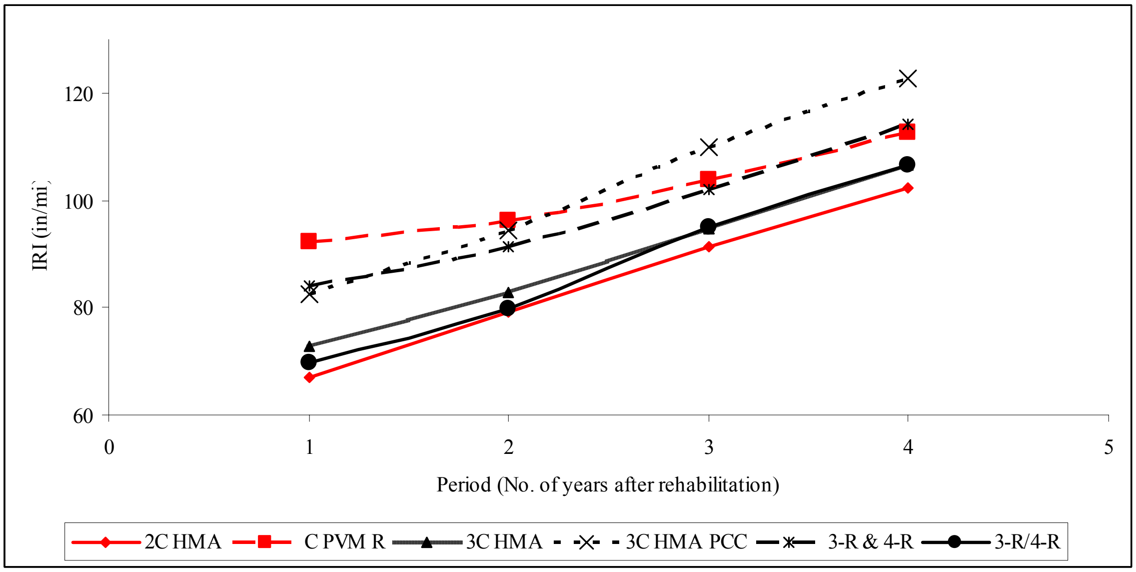

Figure 4.21 Mean IRI in urban interstates for the base year (year 1) and the three consecutive years (years 2, 3, and 4) for each rehabilitation treatment

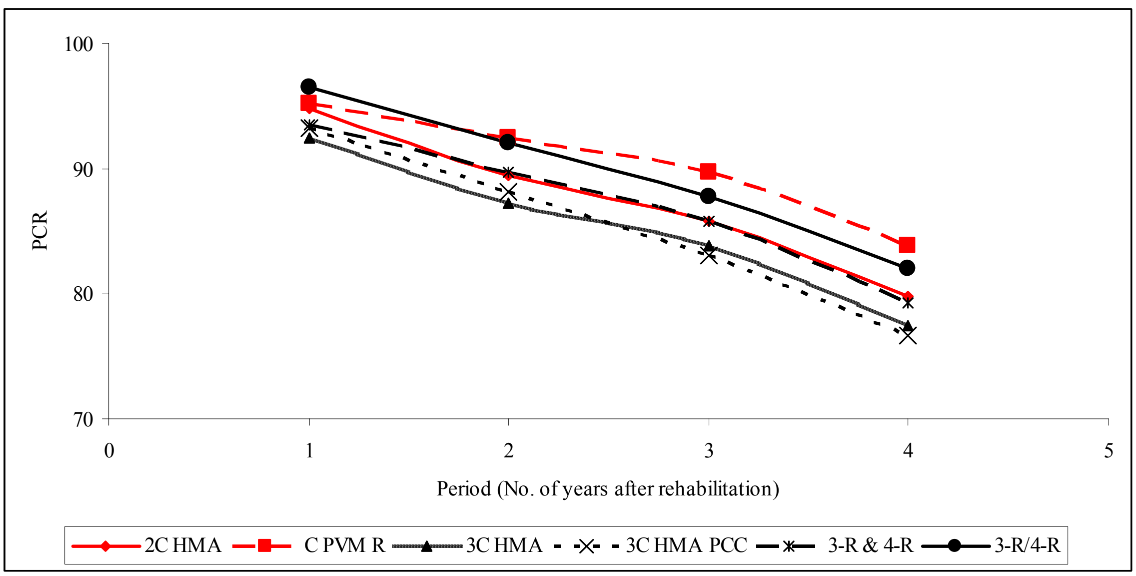

Figure 4.22 Mean PCR in urban interstates for the base year (year 1) and the three consecutive years (years 2, 3, and 4) for each rehabilitation treatment

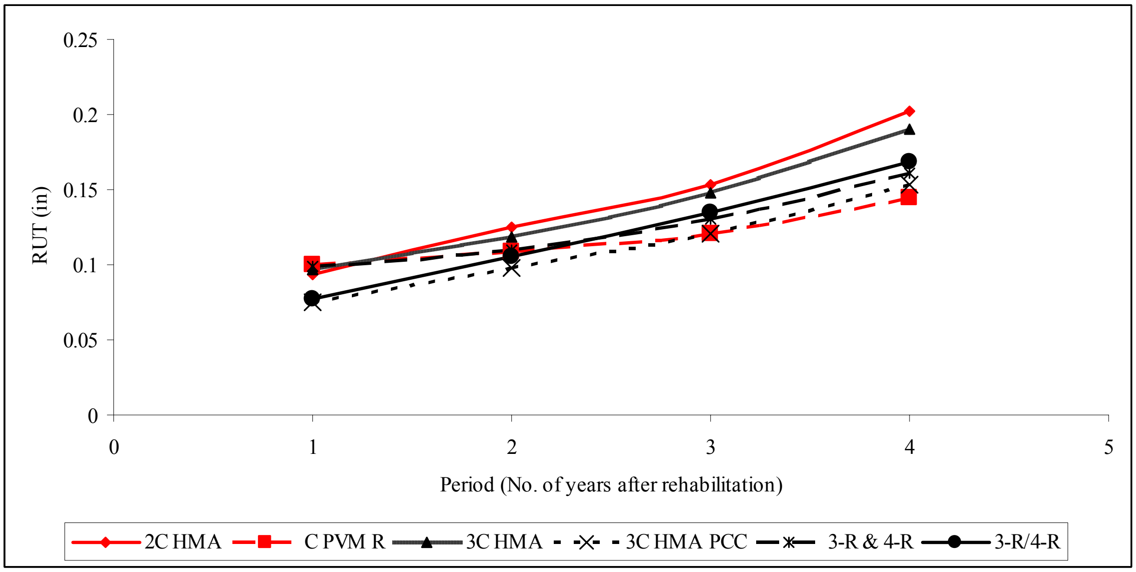

Figure 4.23 Mean rut depth in urban interstates for the base year (year 1) and the three consecutive years (years 2, 3, and 4) for each rehabilitation treatment

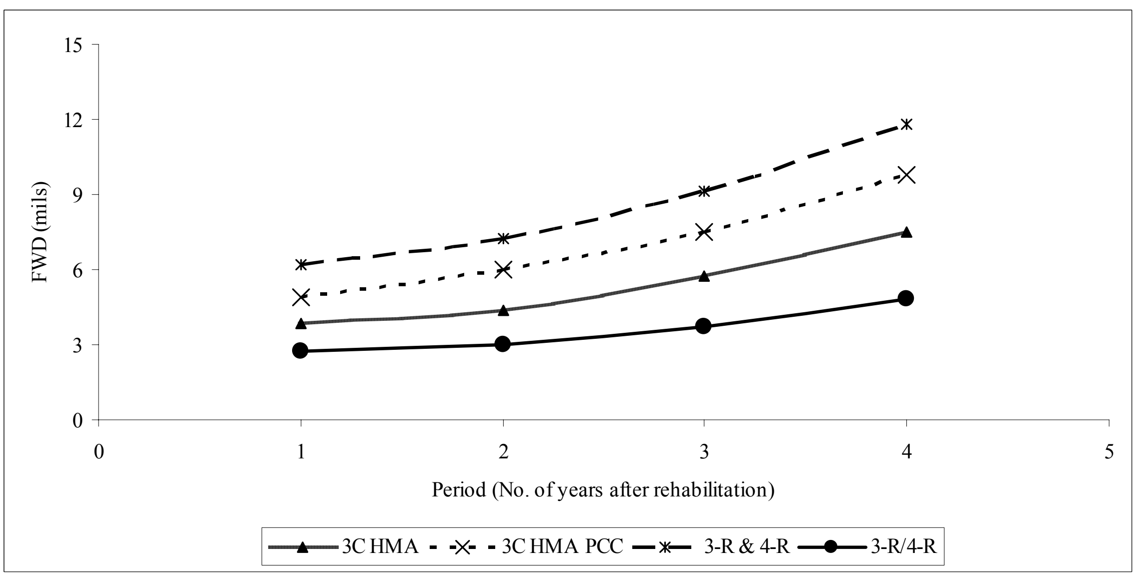

Figure 4.24 Mean deflection in urban interstates for the base year (year 1) and the three consecutive years (years 2, 3, and 4) for each rehabilitation treatment

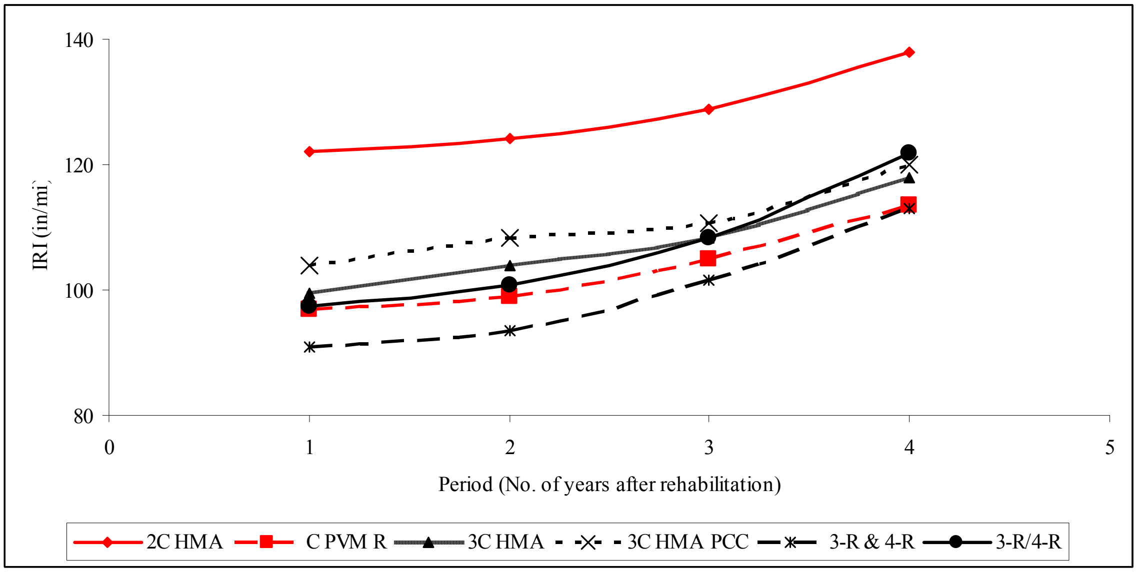

Figure 4.25 Mean IRI in urban non-interstates of the NHS for the base year (year 1) and the three consecutive years (years 2, 3, and 4) for each rehabilitation treatment

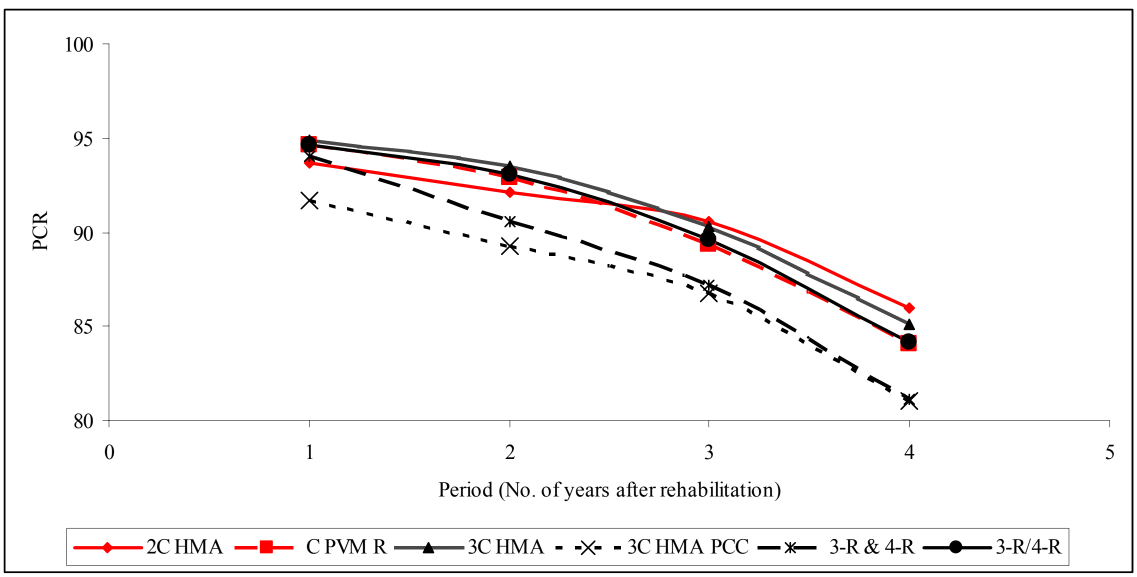

Figure 4.26 Mean PCR in urban non-interstates of the NHS for the base year (year 1) and the three consecutive years (years 2, 3, and 4) for each rehabilitation treatment

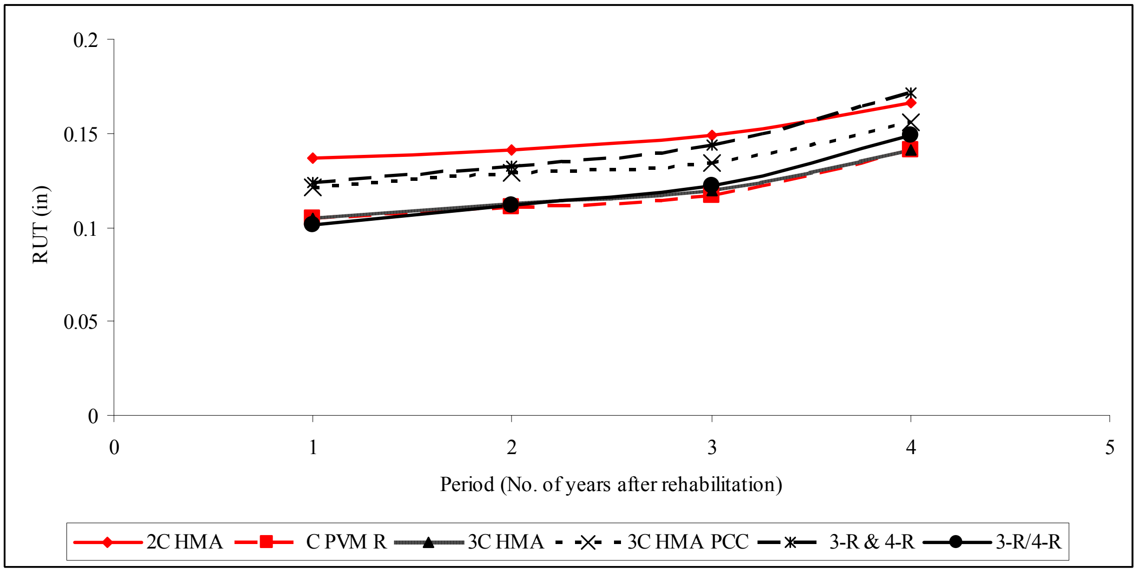

Figure 4.27 Mean rut depth in urban non-interstates of the NHS for the base year (year 1) and the three consecutive years (years 2, 3, and 4) for each rehabilitation treatment

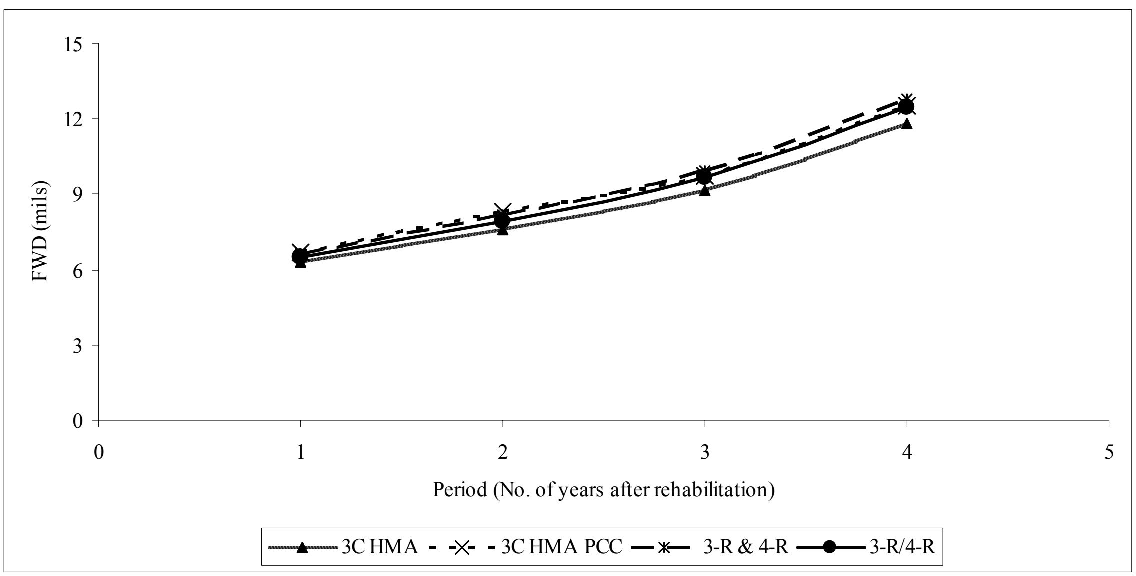

Figure 4.28 Mean deflection in urban non-interstates of the NHS for the base year (year 1) and the three consecutive years (years 2, 3, and 4) for each rehabilitation treatment

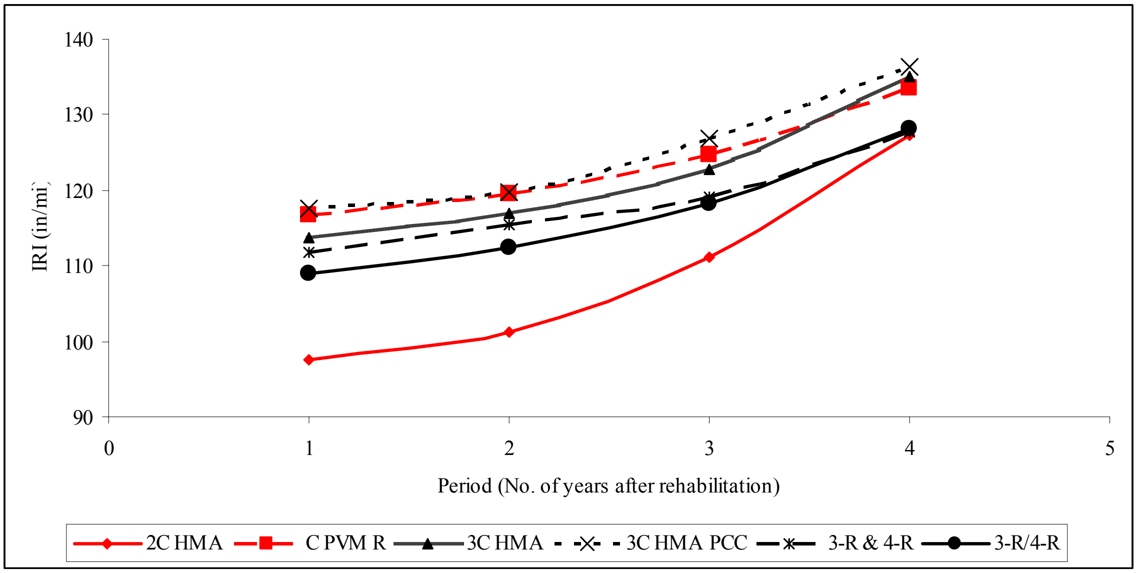

Figure 4.29 Mean IRI in urban non-interstates non-NHS for the base year (year 1) and the three consecutive years (years 2, 3, and 4) for each rehabilitation treatment

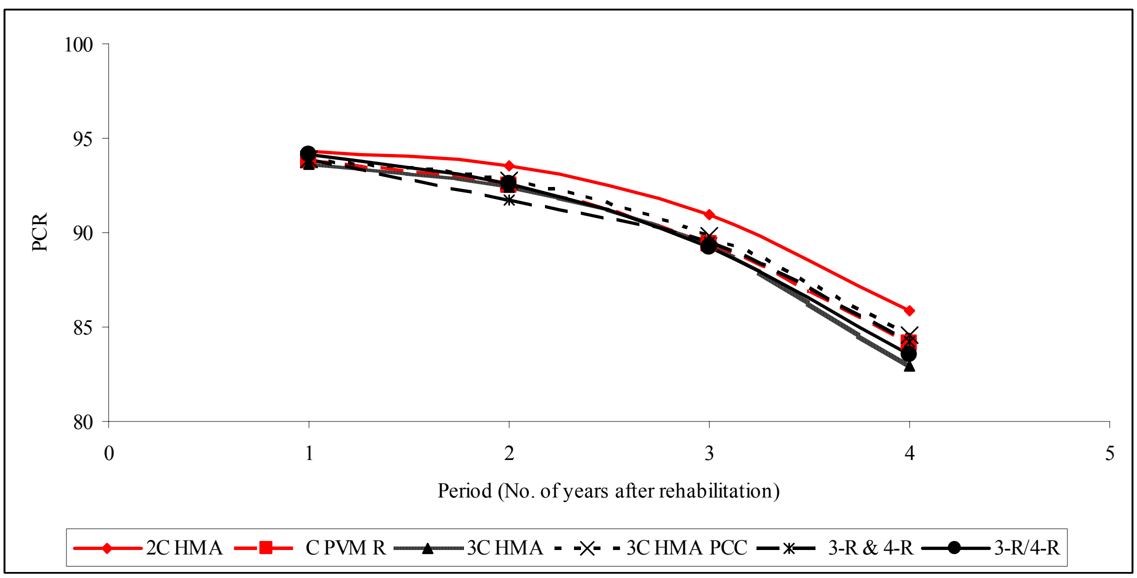

Figure 4.30 Mean PCR in urban non-interstates non-NHS for the base year (year 1) and the three consecutive years (years 2, 3, and 4) for each rehabilitation treatment

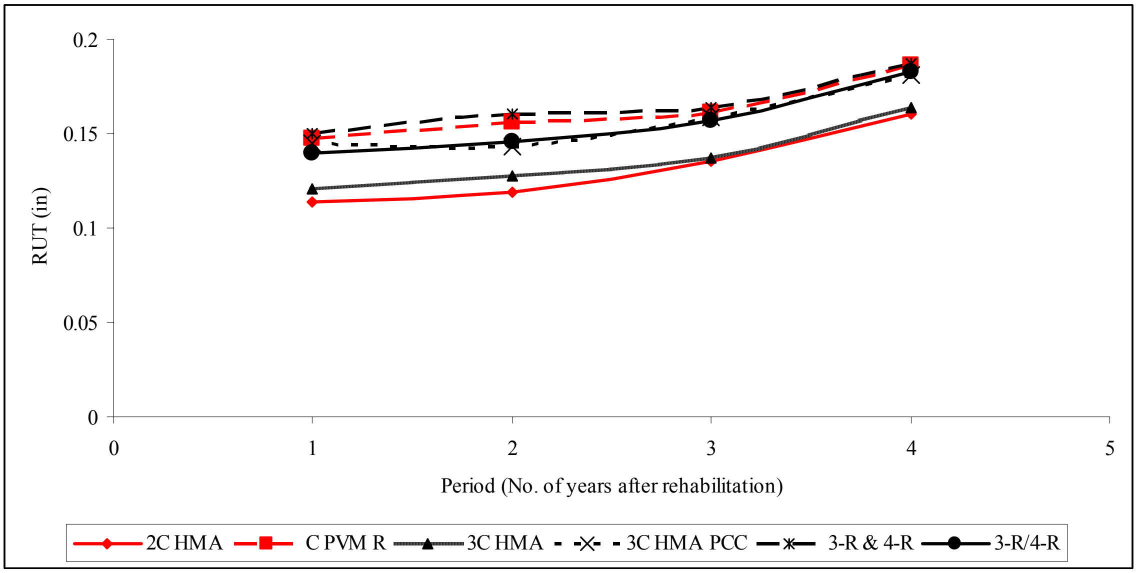

Figure 4.31 Mean rut depth in urban non-interstates non-NHS for the base year (year 1) and the three consecutive years (years 2, 3, and 4) for each rehabilitation treatment

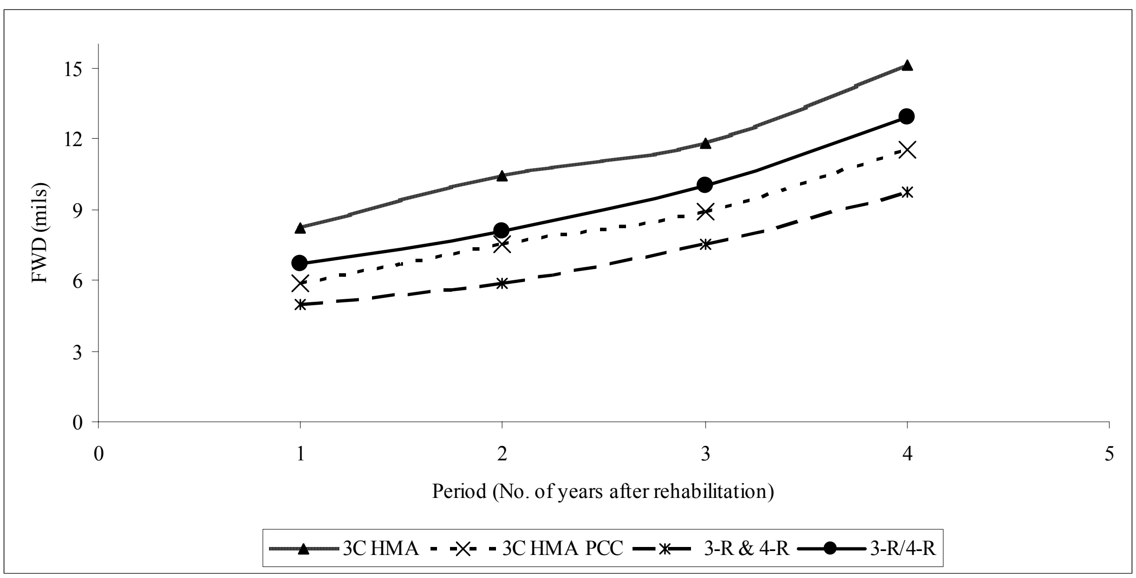

Figure 4.32 Mean deflection in urban non-interstates non-NHS for the base year (year 1) and the three consecutive years (years 2, 3, and 4) for each rehabilitation treatment

Although the mean values of the pavement condition indicators illustrated in Figures 4.9 through 4.32 represent different samples of pavement sections with different traffic volumes, weather and soil conditions, and drainage classifications, there are some general trends from the pavement condition deterioration over time that can be observed. Those are described below.

- Rural interstates: Over the four-year period, 2C HMA has an average deterioration in IRI, PCR, and RUT of 34 in/mi, 14, and 0.1 inches, respectively; and C PVM R of 32 in/mi, 14, and 0.07 inches, respectively. 3C HMA has an average deterioration in IRI, PCR, RUT, and FWD of 25 in/mi, 13, 0.06 inches, and 5.2 mils, respectively; 3C HMA PCC of 33 in/mi, 16, 0.18 inches, and 4.4 mils, respectively; 3-R & 4-R of 32 in/mi, 15, 0.08 inches, and 3.4 mils, respectively; and 3-R/4-R of 33 in/mi, 15, 0.1 inches, and 2.4 mils, respectively.

- Rural non-interstates of the National Highway System: Over the four-year period, 2C HMA has an average deterioration in IRI, PCR, and RUT of 14 in/mi, 10, and 0.04 inches, respectively; and C PVM R of 16 in/mi, 11, and 0.04 inches, respectively. 3C HMA has an average deterioration in IRI, PCR, RUT, and FWD of 18 in/mi, 11, 0.04 inches, and 3.2 mils, respectively; 3C HMA PCC of 15 in/mi, 11, 0.04 inches, and 5.9 mils, respectively; 3-R & 4-R of 16 in/mi, 11, 0.04 inches, and 4.2 mils, respectively; and 3-R/4-R of 15 in/mi, 9, 0.04 inches, and 3.7 mils, respectively.

- Rural non-interstates that do not belong in the National Highway System: Over the four-year period, 2C HMA has an average deterioration in IRI, PCR, and RUT of 20 in/mi, 9, and 0.04 inches, respectively; and C PVM R of 17 in/mi, 10, and 0.04 inches, respectively. 3C HMA has an average deterioration in IRI, PCR, RUT, and FWD of 18 in/mi, 12, 0.04 inches, and 6.2 mils, respectively; 3C HMA PCC of 15 in/mi, 10, 0.04 inches, and 5.8 mils, respectively; 3-R & 4-R of

16 in/mi, 10, 0.03 inches, and 5.4 mils, respectively; and 3-R/4-R of 15 in/mi, 10, 0.04 inches, and 4.1 mils, respectively.

- Urban interstates: Over the four-year period, 2C HMA has an average deterioration in IRI, PCR, and RUT of 35 in/mi, 15, and 0.11 inches, respectively; and C PVM R of 20 in/mi, 11, and 0.05 inches, respectively. 3C HMA has an average deterioration in IRI, PCR, RUT, and FWD of 34 in/mi, 15, 0.09 inches, and 3.6 mils, respectively; 3C HMA PCC of 40 in/mi, 17, 0.08 inches, and 4.8 mils, respectively; 3-R & 4-R of 30 in/mi, 14, 0.06 inches, and 5.6 mils, respectively; and 3-R/4-R of 37 in/mi, 14, 0.09 inches, and 2.1 mils, respectively.

- Urban non-interstates of the National Highway System: Over the four-year period, 2C HMA has an average deterioration in IRI, PCR, and RUT of 16 in/mi, 8, and 0.03 inches, respectively; and C PVM R of 17 in/mi, 11, and 0.04 inches, respectively. 3C HMA has an average deterioration in IRI, PCR, RUT, and FWD of 18 in/mi, 10, 0.04 inches, and 5.5 mils, respectively; 3C HMA PCC of 16 in/mi, 11, 0.04 inches, and 5.8 mils, respectively; 3-R & 4-R of 22 in/mi, 13, 0.05 inches, and 6.1 mils, respectively; and 3-R/4-R of 25 in/mi, 10, 0.05 inches, and 6 mils, respectively.

- Urban non-interstates that do not belong in the National Highway System: Over the four-year period, 2C HMA has an average deterioration in IRI, PCR, and RUT of 29 in/mi, 8, and 0.05 inches, respectively; and C PVM R of 17 in/mi, 10, and 0.04 inches, respectively. 3C HMA has an average deterioration in IRI, PCR, RUT, and FWD of 21 in/mi, 11, 0.04 inches, and 6.9 mils, respectively; 3C HMA PCC of 19 in/mi, 9, 0.04 inches, and 5.7 mils, respectively; 3-R & 4-R of 16 in/mi, 10, 0.04 inches, and 4.8 mils, respectively; and 3-R/4-R of 19 in/mi, 11, 0.04 inches, and 6.2 mils, respectively.

4.3. Pavement Performance Model Results

The following sections present and discuss the model estimation results of the six rehabilitation treatments[30] for the six road functional classes. Note that for each pavement section, two points in time between two consecutive treatments are selected (Figure 4.33). Then, the road sections are grouped into 36 categories, each one representing one of the six rehabilitation treatment for each of the six road functional class.

Variables that are found to be significant in the models are the following (given that the analysis is conducted in period t):

- Base (right after treatment) IRI (in/mi) - IRI base;
- Base (right after treatment) PCR - PCR base;
- Base (right after treatment) rut depth (inches) - RUT base;
- Base (right after treatment) surface deflection (mils) - FWD base;
- IRI in period t-1 (in/mi) - IRI t-1;
- PCR in period t-1 - PCR t-1;
- Rut depth in period t-1 (inches) - RUT t-1;
- Surface deflection in period t-1 (mils) - FWD t-1;
- Cumulative (over treatment study period) daily number of trucks - Trucks;
- Drainage classification: (i) excessively or somewhat excessively drained - DR 1, (ii) excessively, somewhat excessively, or well drained - DR 2, (iii) excessively, somewhat excessively, well, or moderately well drained - DR 3, (iv) somewhat poorly, poorly, or very poorly drained - DR 4, and (v) poorly or very poorly drained - DR 5;
- Treatment contract final cost per lane-mile (in U.S. dollars - USD) - Cost; and
- Indicator variable for treatment contract final cost per lane-mile (1 if less than 50,000 USD, 0 otherwise) - Cost 50K.

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[30] Note that indicator variables representing surface milling were tested in the models, and they are all found to be statistically insignificant. This indicates that surface milling does not play an important role in determining pavement condition (with respect to the sample data), and justifies the grouping of HMA overlays with and without surface milling.

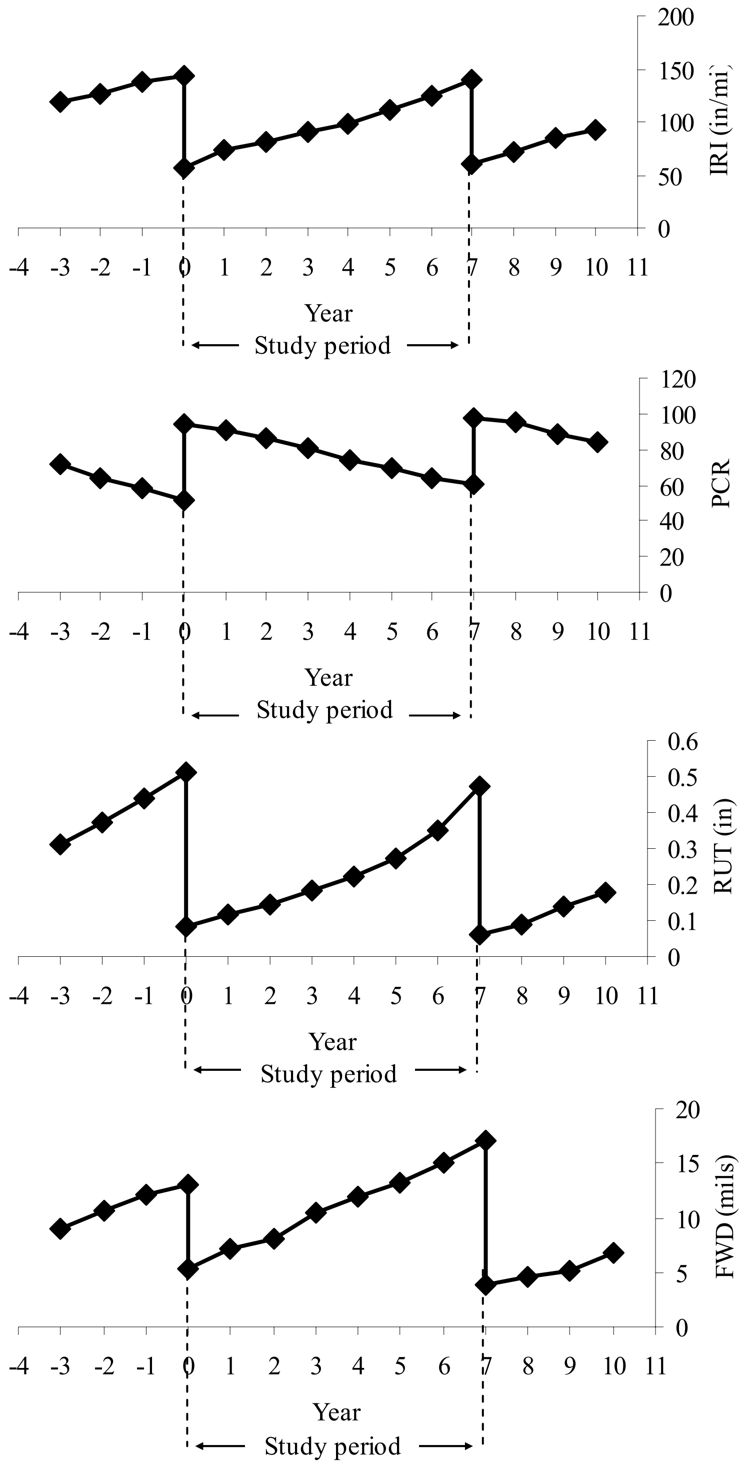

Figure 4.33 Representation of the study period determination for each observation

Note that the cumulative, over the treatment study period n, daily number of trucks (T_n) is estimated as follows:

$$T_n = \sum_n TRUCKS = 365 \cdot \sum_{i=1}^{n} AADT_i \cdot C_i \, , \qquad (6)$$

where, $AADT_i$ is the average daily annual traffic for year i, and C_i the percentage of commercial trucks for the same year i. Also, all monetary amounts are converted and expressed in year 2007 USD prices (1987 base), using the Price Trends for Federal-Aid Highway Construction (Sinha and Labi, 2007):

$$M^* = M_{ref} \times \frac{I^*}{I_{ref}} \, , \qquad (7)$$

where, M^* is the monetary cost in any year, M_{ref} the monetary cost in a reference year, I^* the price index for the year of the M^*, and I_{ref} the price index for the reference year. As a final point, to avoid serious endogeneity problems from the inclusion of the pavement condition lag (t-1) variables, the latter ones are regressed against only exogenous variables, and their predicted values are used instead of the actual t-1 variables. As such, the t-1 lag variables are instruments of the actual lag pavement condition variables.

4.3.1. Rural Roads: Interstates

Tables 4.4 through 4.9 and Equations (8) through (13) present the model results for the SURE rural interstate models of the two-course hot-mix asphalt (HMA) overlay with or without surface milling, concrete pavement restoration, three-course HMA overlay with or without surface milling; three-course HMA overlay with crack and seat of Portland cement concrete (PCC) pavement, 3-R (resurfacing, restoration and rehabilitation) and 4-R (resurfacing, restoration, rehabilitation and reconstruction) overlay treatments, and 3-R/4-R pavement replacement treatments, respectively.

Table 4.4 Two-course HMA overlay with or without surface milling SURE

Dependent variable: IRI t	Coefficient	*t*-stat	P-value
IRI t-1	1.0753	110.6570	0.0000
Trucks (in 100,000s)	0.0307	2.9920	0.0028
Cost (in million USD)	-9.5564	-3.6250	0.0003
R-square	0.9411		
Adjusted R-square	0.9408		
Dependent variable: PCR t	Coefficient	*t*-stat	P-value
Constant	-8.3983	-3.8340	0.0001
PCR base	0.0717	2.1320	0.0330
PCR t-1	0.9781	40.7510	0.0000
Trucks (in 100,000s)	-0.0048	-2.5330	0.0113
DR 2	0.6120	1.7020	0.0888
R-square	0.8241		
Adjusted R-square	0.8227		
Dependent variable: RUT t	Coefficient	*t*-stat	P-value
RUT base	0.0694	5.6570	0.0000
RUT t-1	1.0965	19.2390	0.0000
Trucks (in 100,000s)	0.0001	3.5080	0.0005
R-square	0.8240		
Adjusted R-square	0.8226		
System's R-square	0.8631		
System's Adjusted R-square	0.8620		
Number of observations	495		

$$
\begin{aligned}
IRI_t &= 1.0753 \cdot IRI_{t-1} + 0.0307 \cdot Trucks - 0.95564 \cdot Cost \\
PCR_t &= -8.3983 + 0.0717 \cdot PCR_{base} + 0.9781 \cdot PCR_{t-1} - 0.0048 \cdot Trucks \\
&\quad + 0.612 \cdot DR2 \\
RUT_t &= 0.0694 \cdot RUT_{base} + 1.0965 \cdot RUT_{t-1} + 0.0001 \cdot Trucks
\end{aligned}
\tag{8}
$$

Table 4.5 Concrete pavement restoration SURE

Dependent variable: IRI t	Coefficient	*t*-stat	P-value
Constant	5.2066	3.6370	0.0003
IRI base	0.0820	6.8840	0.0000
IRI t-1	1.0006	43.8540	0.0000
Trucks (in 100,000s)	0.0161	2.9110	0.0036
DR 2	-4.1409	-2.9470	0.0032
Cost 50K	2.0078	2.7820	0.0054
R-square	0.9667		
Adjusted R-square	0.9662		
Dependent variable: PCR t	Coefficient	*t*-stat	P-value
Constant	-1.8716	-2.7170	0.0066
PCR t-1	0.9786	48.8220	0.0000
Trucks (in 100,000s)	-0.0017	-3.0240	0.0025
R-square	0.8682		
Adjusted R-square	0.8675		
Dependent variable: RUT t	Coefficient	*t*-stat	P-value
Constant	0.0287	5.0550	0.0000
RUT base	0.0777	2.0030	0.0452
RUT t-1	1.0554	40.3420	0.0000
DR 2	-0.0046	-1.8340	0.0666
Cost 50K	0.0022	1.6980	0.0895
R-square	0.9318		
Adjusted R-square	0.9310		
System's R-square	0.9222		
System's Adjusted R-square	0.9216		
Number of observations	370		

$$\begin{aligned}
IRI_t &= 5.2066 + 0.082 \cdot IRI_{base} + 1.0006 \cdot IRI_{t-1} + 0.0161 \cdot Trucks \\
&\quad - 4.1409 \cdot DR2 + 2.0078 \cdot Cost50K \\
PCR_t &= -1.8716 + 0.9786 \cdot PCR_{t-1} - 0.0017 \cdot Trucks \\
RUT_t &= 0.0287 + 0.0777 \cdot RUT_{base} + 1.0554 \cdot RUT_{t-1} - 0.046 \cdot DR2 \\
&\quad + 0.0022 \cdot Cost50K
\end{aligned} \tag{9}$$

Table 4.6 Three-course HMA overlay with or without surface milling SURE

Dependent variable: IRI t	Coefficient	*t*-stat	P-value
IRI base	0.1246	5.1030	0.0000
IRI t-1	1.0014	44.6250	0.0000
Trucks (in 100,000s)	0.0059	5.6540	0.0000
DR 5	2.0419	2.6130	0.0090
R-square	0.9195		
Adjusted R-square	0.9191		
Dependent variable: PCR t	Coefficient	*t*-stat	P-value
Constant	-7.8975	-4.0320	0.0001
PCR base	0.0853	2.9330	0.0034
PCR t-1	0.9419	43.6680	0.0000
R-square	0.8200		
Adjusted R-square	0.8194		
Dependent variable: RUT t	Coefficient	*t*-stat	P-value
Constant	0.0141	4.6560	0.0000
RUT t-1	1.1456	97.6790	0.0000
Trucks (in 100,000s)	0.0001	1.7560	0.0790
DR 5	0.0045	1.6590	0.0972
R-square	0.9342		
Adjusted R-square	0.9338		
Dependent variable: FWD t	Coefficient	*t*-stat	P-value
FWD base	-0.1672	-9.3450	0.0000
FWD t-1	1.2060	120.6190	0.0000
Trucks (in 100,000s)	0.0006	4.7470	0.0000
DR 5	0.0808	2.4850	0.0129
R-square	0.9961		
Adjusted R-square	0.9961		
System's R-square	0.9174		
System's Adjusted R-square	0.9171		
Number of observations	649		

$$
\begin{aligned}
IRI_t &= 0.1246 \cdot IRI_{base} + 1.0014 \cdot IRI_{t-1} + 0.0059 \cdot Trucks + 2.0419 \cdot DR5 \\
PCR_t &= -7.8975 + 0.0853 \cdot PCR_{base} + 0.9419 \cdot PCR_{t-1} \\
RUT_t &= 0.0141 + 1.1456 \cdot RUT_{t-1} + 0.0001 \cdot Trucks + 0.0045 \cdot DR5 \\
FWD_t &= -0.1672 \cdot FWD_{base} + 1.206 \cdot FWD_{t-1} + 0.0006 \cdot Trucks + 0.0808 \cdot DR5
\end{aligned}
\tag{10}
$$

Table 4.7 Three-course HMA overlay with crack and seat of PCC pavement SURE

Dependent variable: IRI t	Coefficient	*t*-stat	P-value
IRI base	0.1319	3.9100	0.0001
IRI t-1	0.9923	27.3600	0.0000
Trucks (in 100,000)	0.0170	3.4600	0.0005
DR 5	1.7042	1.7900	0.0734
Cost (in million USD)	-1.5813	-1.9490	0.0513
R-square	0.9262		
Adjusted R-square	0.9247		
Dependent variable: PCR t	Coefficient	*t*-stat	P-value
PCR t-1	0.9726	116.0760	0.0000
Trucks (in 100,000s)	-0.0085	-1.7680	0.0770
R-square	0.8583		
Adjusted R-square	0.8577		
Dependent variable: RUT t	Coefficient	*t*-stat	P-value
Constant	0.0172	3.0120	0.0026
RUT base	0.0940	3.5750	0.0004
RUT t-1	1.0023	23.0530	0.0000
Trucks (in 100,000s)	0.0002	2.1100	0.0348
DR 5	0.0907	2.1160	0.0344
R-square	0.7668		
Adjusted R-square	0.7623		
Dependent variable: FWD t	Coefficient	*t*-stat	P-value
FWD base	-0.1161	-4.7110	0.0000
FWD t-1	1.1462	98.3880	0.0000
Trucks (in 100,000s)	0.0009	3.7520	0.0002
R-square	0.9982		
Adjusted R-square	0.9982		
System's R-square	0.8874		
System's Adjusted R-square	0.8857		
Number of observations	209		

$$\begin{aligned}
IRI_t &= 0.1319 \cdot IRI_{base} + 0.9923 \cdot IRI_{t-1} + 0.0170 \cdot Trucks + 1.7042 \cdot DR5 \\
&\quad - 1.5813 \cdot Cost \\
PCR_t &= 0.9726 \cdot PCR_{t-1} - 0.0085 \cdot Trucks \\
RUT_t &= 0.0172 + 0.094 \cdot RUT_{base} + 1.0023 \cdot RUT_{t-1} + 0.0002 \cdot Trucks \\
&\quad + 0.0907 \cdot DR5 \\
FWD_t &= -0.11161 \cdot FWD_{base} + 1.1462 \cdot FWD_{t-1} + 0.0009 \cdot Trucks
\end{aligned} \tag{11}$$

Table 4.8 3-R and 4-R overlay treatments SURE

Dependent variable: IRI t	Coefficient	*t*-stat	P-value
IRI base	0.0554	2.2130	0.0269
IRI t-1	1.0220	46.2860	0.0000
Trucks (in 100,000s)	0.0103	6.6140	0.0000
Cost (in million USD)	-0.2357	-2.6600	0.0078
R-square	0.9672		
Adjusted R-square	0.9667		
Dependent variable: PCR t	Coefficient	*t*-stat	P-value
Constant	-0.9626	-2.2760	0.0229
PCR t-1	0.9980	33.1970	0.0000
Trucks (in 100,000s)	-0.0138	-3.7460	0.0002
DR 5	-1.3369	-2.5320	0.0113
R-square	0.8580		
Adjusted R-square	0.8557		
Dependent variable: RUT t	Coefficient	*t*-stat	P-value
Constant	0.0209	3.8760	0.0001
RUT base	0.1241	2.6600	0.0078
RUT t-1	1.0442	27.1930	0.0000
Trucks (in 100,000s)	0.0001	3.1460	0.0017
DR 3	-0.0108	-3.2690	0.0011
Cost (in million USD)	-0.0065	-1.8220	0.0685
R-square	0.9431		
Adjusted R-square	0.9416		
Dependent variable: FWD t	Coefficient	*t*-stat	P-value
FWD base	-0.1434	-5.6600	0.0000
FWD t-1	1.1699	87.0220	0.0000
Trucks (in 100,000s)	0.0006	4.1610	0.0000
DR 5	0.0585	1.7000	0.0891
Cost (in million USD)	-0.0613	-1.9380	0.0526
R-square	0.9973		
Adjusted R-square	0.9972		
System's R-square	0.9414		
System's Adjusted R-square	0.9403		
Number of observations	193		

$$
\begin{aligned}
IRI_t &= 0.0554 \cdot IRI_{base} + 1.022 \cdot IRI_{t-1} + 0.0103 \cdot Trucks - 0.2357 \cdot Cost \\
PCR_t &= -0.9626 + 0.998 \cdot PCR_{t-1} - 0.0138 \cdot Trucks - 1.3369 \cdot DR5 \\
RUT_t &= 0.0209 + 0.1241 \cdot RUT_{base} + 1.0442 \cdot RUT_{t-1} + 0.0001 \cdot Trucks \\
&\quad - 0.0108 \cdot DR3 - 0.0065 \cdot Cost \\
FWD_t &= -0.1434 \cdot FWD_{base} + 1.1699 \cdot FWD_{t-1} + 0.0006 \cdot Trucks - 0.0613 \cdot Cost
\end{aligned}
\tag{12}
$$

Table 4.9 3-R/4-R pavement replacement treatments SURE

Dependent variable: IRI t	Coefficient	*t*-stat	P-value
Constant	1.0413	3.3930	0.0007
IRI base	0.0522	2.8730	0.0041
IRI t-1	1.0044	40.5240	0.0000
Trucks (in 100,000s)	0.0149	2.0480	0.0406
Cost (in million USD)	-0.8565	-2.1120	0.0347
R-square	0.9642		
Adjusted R-square	0.9636		
Dependent variable: PCR t	Coefficient	*t*-stat	P-value
PCR t-1	0.9496	256.2490	0.0000
DR 5	-1.4209	-3.0620	0.0022
Cost (in million USD)	1.3418	3.7100	0.0002
R-square	0.8506		
Adjusted R-square	0.8493		
Dependent variable: RUT t	Coefficient	*t*-stat	P-value
Constant	0.0248	7.7420	0.0000
RUT t-1	1.0330	43.3190	0.0000
Trucks (in 100,000s)	0.0002	4.5670	0.0000
Cost 50K	0.0085	3.5420	0.0004
R-square	0.9152		
Adjusted R-square	0.9141		
Dependent variable: FWD t	Coefficient	*t*-stat	P-value
Constant	0.1284	2.0140	0.0440
FWD base	-0.0737	-2.9660	0.0030
FWD t-1	1.0922	81.1240	0.0000
Trucks (in 100,000s)	0.0004	2.0450	0.0409
DR 5	0.0556	2.2730	0.0230
Cost (in million USD)	-0.0487	-2.4370	0.0148
R-square	0.9820		
Adjusted R-square	0.9816		
System's R-square	0.9280		
System's Adjusted R-square	0.9271		
Number of observations	232		

$$
\begin{aligned}
IRI_t &= 1.0413 + 0.0522 \cdot IRI_{base} + 1.0044 \cdot IRI_{t-1} + 0.0149 \cdot Trucks - 0.8565 \cdot Cost \\
PCR_t &= 0.9496 \cdot PCR_{t-1} - 1.4209 \cdot DR5 + 1.3418 \cdot Cost \\
RUT_t &= 0.0248 + 1.033 \cdot RUT_{t-1} + 0.0002 \cdot Trucks + 0.0085 \cdot Cost50K \\
FWD_t &= 0.1284 - 0.0737 \cdot FWD_{base} + 1.0922 \cdot FWD_{t-1} + 0.0004 \cdot Trucks \\
&\quad + 0.0556 \cdot DR5 - 0.0487 \cdot Cost
\end{aligned} \tag{13}
$$

4.3.2. Rural Roads: Non-Interstates NHS

Tables 4.10 through 4.15 and Equations (14) through (19) present the model results for the SURE rural non-interstate of the NHS models of the six rehabilitation treatments.

Table 4.10 Two-course HMA overlay with or without surface milling SURE

Dependent variable: IRI t	Coefficient	*t* -stat	P-value
IRI t-1	1.0786	277.7270	0.0000
Trucks (in 100,000s)	0.0133	3.2560	0.0011
Cost 50K	1.7587	2.8570	0.0043
R-square	0.9715		
Adjusted R-square	0.9714		
Dependent variable: PCR t	Coefficient	*t* -stat	P-value
Constant	-5.8139	-5.1340	0.0000
PCR t-1	1.0219	50.0050	0.0000
DR 5	-1.3267	-3.0830	0.0021
Cost (in million USD)	0.6973	3.4770	0.0005
R-square	0.8098		
Adjusted R-square	0.8088		
Dependent variable: RUT t	Coefficient	*t* -stat	P-value
Constant	0.0269	2.9050	0.0037
RUT t-1	1.0378	95.3310	0.0000
Trucks (in 100,000s)	0.0001	2.2920	0.0219
DR 5	0.0069	2.4390	0.0147
R-square	0.9322		
Adjusted R-square	0.9318		
System's R-square	0.9045		
System's Adjusted R-square	0.9040		
Number of observations	573		

$$
\begin{aligned}
IRI_t &= 1.0786 \cdot IRI_{t-1} + 0.0133 \cdot Trucks + 1.7587 \cdot Cost50K \\
PCR_t &= -5.8139 + 1.0219 \cdot PCR_{t-1} - 1.3267 \cdot DR5 + 0.6973 \cdot Cost \\
RUT_t &= 0.0269 + 1.0378 \cdot RUT_{t-1} + 0.0001 \cdot Trucks + 0.0069 \cdot DR5
\end{aligned} \tag{14}
$$

Table 4.11 Concrete pavement restoration SURE

Dependent variable: IRI t	Coefficient	*t*-stat	P-value
IRI t-1	1.0351	231.7700	0.0000
Trucks (in 100,000s)	0.0382	1.7530	0.0797
DR 5	5.6599	5.8490	0.0000
R-square	0.9682		
Adjusted R-square	0.9679		
Dependent variable: PCR t	Coefficient	*t*-stat	P-value
Constant	-12.8432	-3.3370	0.0008
PCR base	0.0958	1.9480	0.0514
PCR t-1	0.9999	25.3440	0.0000
DR 5	-1.3262	-2.1420	0.0322
R-square	0.7828		
Adjusted R-square	0.7803		
Dependent variable: RUT t	Coefficient	*t*-stat	P-value
RUT base	-0.0983	-2.2080	0.0273
RUT t-1	1.1011	19.4590	0.0000
Trucks (in 100,000s)	0.0002	3.3940	0.0007
DR 5	0.0064	1.7530	0.0796
Cost 50K	0.0099	3.8930	0.0001
R-square	0.9327		
Adjusted R-square	0.9316		
System's R-square	0.8946		
System's Adjusted R-square	0.8933		
Number of observations	264		

$$
\begin{aligned}
IRI_t &= 1.0351 \cdot IRI_{t-1} + 0.0382 \cdot Trucks + 5.6599 \cdot DR5 \\
PCR_t &= -12.8432 + 0.0958 \cdot PCR_{base} + 0.9999 \cdot PCR_{t-1} - 1.3262 \cdot DR5 \\
RUT_t &= -0.0983 \cdot RUT_{base} + 1.1011 \cdot RUT_{t-1} + 0.0002 \cdot Trucks \\
&\quad + 0.0064 \cdot DR5 + 0.0099 \cdot Cost50K
\end{aligned}
\tag{15}
$$

Table 4.12 Three-course HMA overlay with or without surface milling SURE

Dependent variable: IRI t	Coefficient	*t*-stat	P-value
Constant	6.8757	8.4110	0.0000
IRI t-1	0.9887	126.5490	0.0000
Trucks (in 100,000s)	0.0219	4.4360	0.0000
Cost 50K	2.7303	3.6460	0.0003
R-square	0.9708		
Adjusted R-square	0.9706		
Dependent variable: PCR t	Coefficient	*t*-stat	P-value
Constant	-1.9948	-4.8730	0.0000
PCR t-1	0.9981	41.9630	0.0000
Trucks (in 100,000s)	-0.0211	-2.7110	0.0067
DR 2	1.3687	3.4150	0.0006
Cost 50K	-0.9914	-1.8730	0.0611
R-square	0.8416		
Adjusted R-square	0.8400		
Dependent variable: RUT t	Coefficient	*t*-stat	P-value
Constant	0.0082	7.2260	0.0000
RUT base	-0.1016	-3.1220	0.0018
RUT t-1	1.1189	24.4410	0.0000
Trucks (in 100,000s)	0.0002	2.6010	0.0093
DR 3	-0.0047	-2.3180	0.0204
R-square	0.9620		
Adjusted R-square	0.9616		
Dependent variable: FWD t	Coefficient	*t*-stat	P-value
FWD base	-0.1462	-7.6220	0.0000
FWD t-1	1.1782	105.4980	0.0000
Trucks (in 100,000s)	0.0016	3.7370	0.0002
DR 3	-0.0346	-1.9600	0.0500
R-square	0.9955		
Adjusted R-square	0.9955		
System's R-square	0.9425		
System's Adjusted R-square	0.9419		
Number of observations	412		

$$
\begin{aligned}
IRI_t &= 6.8757 + +0.9887 \cdot IRI_{t-1} + 0.0219 \cdot Trucks + 2.7303 \cdot Cost50K \\
PCR_t &= -1.9948 + 0.9981 \cdot PCR_{t-1} - 0.0211 \cdot Trucks + 1.3687 \cdot DR2 \\
&\quad - 0.9914 \cdot Cost50K \\
RUT_t &= 0.008 - 0.102 \cdot RUT_{base} + 1.119 \cdot RUT_{t-1} + 0.0002 \cdot Trucks \\
&\quad - 0.0047 \cdot DR3 \\
FWD_t &= -0.1462 \cdot FWD_{base} + 1.1782 \cdot FWD_{t-1} + 0.0016 \cdot Trucks - 0.0346 \cdot DR3
\end{aligned} \tag{16}
$$

Table 4.13 Three-course HMA overlay with crack and seat of PCC pavement SURE

Dependent variable: IRI t	Coefficient	*t* -stat	P-value
Constant	3.0540	6.4700	0
IRI t-1	1.0017	174.1320	0
Trucks (in 100,000s)	0.0368	3.6460	0.0003
DR 5	4.4415	2.9520	0.0032
R-square	0.9656		
Adjusted R-square	0.9653		
Dependent variable: PCR t	Coefficient	*t* -stat	P-value
PCR base	-0.0137	-2.1690	0.0301
PCR t-1	0.9670	20.8840	0.0000
R-square	0.8444		
Adjusted R-square	0.8437		
Dependent variable: RUT t	Coefficient	*t* -stat	P-value
Constant	0.0172	4.4280	0.0000
RUT base	0.0120	5.2170	0.0000
RUT t-1	1.0422	96.0280	0.0000
Trucks (in 100,000s)	0.0002	3.5090	0.0004
DR 5	0.0907	5.3640	0.0000
R-square	0.9287		
Adjusted R-square	0.9284		
Dependent variable: FWD t	Coefficient	*t* -stat	P-value
FWD base	-0.1320	-5.0070	0.0000
FWD t-1	1.1336	62.2170	0.0000
Trucks (in 100,000s)	0.0033	2.0500	0.0403
R-square	0.9936		
Adjusted R-square	0.9936		
System's R-square	0.9331		
System's Adjusted R-square	0.9327		
Number of observations	205		

$$
\begin{aligned}
IRI_t &= 3.054 + 1.0017 \cdot IRI_{t-1} + 0.0368 \cdot Trucks + 4.4415 \cdot DR5 \\
PCR_t &= -0.0137 \cdot PCR_{base} + 0.967 \cdot PCR_{t-1} \\
RUT_t &= 0.0172 + 0.012 \cdot RUT_{base} + 1.0422 \cdot RUT_{t-1} + 0.0002 \cdot Trucks \\
&\quad + 0.0907 \cdot DR5 \\
FWD_t &= -0.132 \cdot FWD_{base} + 1.1336 \cdot FWD_{t-1} + 0.0033 \cdot Trucks
\end{aligned} \tag{17}
$$

Table 4.14 3-R and 4-R overlay treatments SURE

Dependent variable: IRI t	Coefficient	*t*-stat	P-value
IRI base	0.0846	2.5970	0.0094
IRI t-1	1.0196	31.6400	0.0000
Trucks (in 100,000s)	0.0246	1.8160	0.0694
DR 5	1.2551	3.9610	0.0001
Cost (in million USD)	-0.5610	-2.9440	0.0032
R-square	0.9690		
Adjusted R-square	0.9685		
Dependent variable: PCR t	Coefficient	*t*-stat	P-value
Constant	-2.8343	-4.2660	0.0000
PCR t-1	0.9868	32.9390	0.0000
Cost (in million USD)	1.0532	3.1620	0.0016
R-square	0.8354		
Adjusted R-square	0.8341		
Dependent variable: RUT t	Coefficient	*t*-stat	P-value
Constant	0.0087	5.0700	0.0000
RUT base	-0.0728	-2.8080	0.0050
RUT t-1	1.0726	25.2740	0.0000
Trucks (in 100,000s)	0.0001	2.0900	0.0366
DR 5	0.0091	2.2450	0.0248
Cost (in million USD)	-0.0095	-3.4850	0.0005
R-square	0.9650		
Adjusted R-square	0.9643		
Dependent variable: FWD t	Coefficient	*t*-stat	P-value
FWD base	-0.0342	-1.7350	0.0828
FWD t-1	1.0516	111.4230	0.0000
Trucks (in 100,000s)	0.0021	2.2840	0.0223
R-square	0.9975		
Adjusted R-square	0.9975		
System's R-square	0.9417		
System's Adjusted R-square	0.9411		
Number of observations	250		

$$
\begin{aligned}
IRI_t &= 0.0846 \cdot IRI_{base} + 1.0196 \cdot IRI_{t-1} + 0.0246 \cdot Trucks + 1.2551 \cdot DR5 \\
&\quad - 0.561 \cdot Cost \\
PCR_t &= -2.8343 + 0.9868 \cdot PCR_{t-1} + 1.0532 \cdot Cost \\
RUT_t &= 0.0087 - 0.0728 \cdot RUT_{base} + 1.0726 \cdot RUT_{t-1} + 0.0001 \cdot Trucks \\
&\quad + 0.0091 \cdot DR5 - 0.0095 \cdot Cost \\
FWD_t &= -0.0342 \cdot FWD_{base} + 1.0516 \cdot FWD_{t-1} + 0.0021 \cdot Trucks
\end{aligned}
\tag{18}
$$

Table 4.15 3-R/4-R pavement replacement treatments SURE

Dependent variable: IRI t	Coefficient	*t*-stat	P-value
IRI base	0.0312	2.0700	0.0385
IRI t-1	1.0597	25.4450	0.0000
R-square	0.9518		
Adjusted R-square	0.9516		
Dependent variable: PCR t	Coefficient	*t*-stat	P-value
Constant	-16.4931	-5.3160	0.0000
PCR base	0.1200	1.8180	0.0690
PCR t-1	1.0214	18.6420	0.0000
R-square	0.8423		
Adjusted R-square	0.8411		
Dependent variable: RUT t	Coefficient	*t*-stat	P-value
RUT base	0.0739	2.7400	0.0061
RUT t-1	1.0676	19.5040	0.0000
Trucks (in 100,000s)	0.0001	1.8390	0.0659
R-square	0.9645		
Adjusted R-square	0.9642		
Dependent variable: FWD t	Coefficient	*t*-stat	P-value
Constant	0.1074	2.1800	0.0292
FWD base	-0.0661	-1.9160	0.0554
FWD t-1	1.0733	74.2890	0.0000
Cost 50K	0.0996	2.1700	0.0300
R-square	0.9954		
Adjusted R-square	0.9953		
System's R-square	0.9385		
System's Adjusted R-square	0.9381		
Number of observations	275		

$$
\begin{aligned}
IRI_t &= 0.0312 \cdot IRI_{base} + 1.0597 \cdot IRI_{t-1} \\
PCR_t &= -16.4931 + 0.12 \cdot PCR_{base} + 1.0214 \cdot PCR_{t-1} \\
RUT_t &= 0.0739 \cdot RUT_{base} + 1.0676 \cdot RUT_{t-1} + 0.0001 \cdot Trucks \\
FWD_t &= 0.1074 - 0.0661 \cdot FWD_{base} + 1.0733 \cdot FWD_{t-1} + 0.0996 \cdot Cost50K
\end{aligned} \tag{19}
$$

4.3.3. Rural Roads: Non-Interstates Non-NHS

Tables 4.16 through 4.21 and Equations (20) through (25) present the model results for the SURE rural non-interstate non-NHS models of the six rehabilitation treatments.

Table 4.16 Two-course HMA overlay with or without surface milling SURE

Dependent variable: IRI t	Coefficient	*t* -stat	P-value
Constant	7.6077	7.6360	0.0000
IRI t-1	1.0160	150.4680	0.0000
Trucks (in 100,000s)	0.0361	2.6180	0.0089
DR 2	-4.0431	-5.9770	0.0000
Cost (in million USD)	-0.9819	-2.2220	0.0263
R-square	0.9142		
Adjusted R-square	0.9140		
Dependent variable: PCR t	Coefficient	*t* -stat	P-value
Constant	-1.4509	-9.0760	0.0000
PCR t-1	0.9561	81.9590	0.0000
DR 2	0.5217	2.5130	0.0120
Cost 50K	-1.2765	-5.7830	0.0000
R-square	0.7844		
Adjusted R-square	0.7841		
Dependent variable: RUT t	Coefficient	*t* -stat	P-value
Constant	0.0094	4.4220	0.0000
RUT base	0.1015	3.3720	0.0007
RUT t-1	1.0006	31.3850	0.0000
Trucks (in 100,000s)	0.0003	6.8240	0.0000
DR 3	-0.0027	-1.9390	0.0525
Cost (in million USD)	-0.0058	-2.0020	0.0453
R-square	0.9071		
Adjusted R-square	0.9069		
System's R-square	0.8686		
System's Adjusted R-square	0.8683		
Number of observations	929		

$$
\begin{aligned}
IRI_t &= 7.6077 + 1.016 \cdot IRI_{t-1} + 0.0361 \cdot Trucks - 4.0431 \cdot DR2 - 0.9819 \cdot Cost \\
PCR_t &= -1.4509 + 0.9561 \cdot PCR_{t-1} + 0.5217 \cdot DR2 - 1.2765 \cdot Cost50K \\
RUT_t &= 0.0094 + 0.1015 \cdot RUT_{base} + 1.0006 \cdot RUT_{t-1} + 0.0003 \cdot Trucks \\
&\quad - 0.0027 \cdot DR3 - 0.0058 \cdot Cost
\end{aligned} \tag{20}
$$

Table 4.17 Concrete pavement restoration SURE

Dependent variable: IRI t	Coefficient	*t* -stat	P-value
IRI base	0.0722	2.6050	0.0092
IRI t-1	0.9855	25.7710	0.0000
Trucks (in 100,000s)	0.0454	2.3790	0.0173
R-square	0.9579		
Adjusted R-square	0.9577		
Dependent variable: PCR t	Coefficient	*t* -stat	P-value
Constant	-2.5228	-1.7370	0.0823
PCR t-1	0.9799	35.7230	0.0000
R-square	0.7726		
Adjusted R-square	0.7719		
Dependent variable: RUT t	Coefficient	*t* -stat	P-value
Constant	0.0104	3.0270	0.0025
RUT t-1	1.2518	64.8460	0.0000
DR 2	-0.0066	-1.7040	0.0883
R-square	0.9114		
Adjusted R-square	0.9109		
System's R-square	0.8806		
System's Adjusted R-square	0.8802		
Number of observations	363		

$$\begin{aligned} IRI_t &= 0.0722 \cdot IRI_{base} + 0.9855 \cdot IRI_{t-1} + 0.0454 \cdot Trucks \\ PCR_t &= -2.5228 + 0.9799 \cdot PCR_{t-1} \\ RUT_t &= 0.0104 + 1.2518 \cdot RUT_{t-1} - 0.0066 \cdot DR2 \end{aligned} \tag{21}$$

Table 4.18 Three-course HMA overlay with or without surface milling SURE

Dependent variable: IRI t	Coefficient	*t* -stat	P-value
Constant	1.6395	6.6370	0.0000
IRI base	0.0508	6.5560	0.0000
IRI t-1	1.0014	30.0650	0.0000
Trucks (in 100,000s)	0.0725	6.0200	0.0000
DR 2	-3.2796	-5.0880	0.0000
Cost (in million USD)	-0.8020	-4.4160	0.0000
R-square	0.9044		
Adjusted R-square	0.9037		
Dependent variable: PCR t	Coefficient	*t* -stat	P-value
PCR base	0.0079	2.9970	0.0027
PCR t-1	0.9859	30.6540	0.0000
Trucks (in 100,000s)	-0.0262	-2.1310	0.0331
Cost (in million USD)	0.2351	2.7930	0.0052
R-square	0.7074		
Adjusted R-square	0.7062		
Dependent variable: RUT t	Coefficient	*t* -stat	P-value
Constant	0.0307	5.1530	0.0000
RUT base	0.0019	5.6800	0.0000
RUT t-1	1.0504	30.2670	0.0000
Trucks (in 100,000s)	0.0002	4.4980	0.0000
DR 5	0.0123	5.5320	0.0000
Cost (in million USD)	-0.0187	-3.5170	0.0004
R-square	0.8906		
Adjusted R-square	0.8898		
Dependent variable: FWD t	Coefficient	*t* -stat	P-value
FWD base	0.0732	7.7180	0.0000
FWD t-1	1.0670	117.6260	0.0000
Trucks (in 100,000s)	0.0038	2.1130	0.0346
DR 5	0.0707	1.9180	0.0551
R-square	0.9962		
Adjusted R-square	0.9962		
System's R-square	0.8746		
System's Adjusted R-square	0.8740		
Number of observations	715		

$$
\begin{aligned}
IRI_t &= 1.64 + 0.05 \cdot IRI_{base} + 1.001 \cdot IRI_{t-1} + 0.07 \cdot Trucks - 3.28 \cdot DR2 - 0.8 \cdot Cost \\
PCR_t &= 0.0079 \cdot PCR_{base} + 0.9859 \cdot PCR_{t-1} - 0.0262 \cdot Trucks + 0.2351 \cdot Cost \\
RUT_t &= 0.03 + 0.002 \cdot RUT_{base} + 1.05 \cdot RUT_{t-1} + 0.0002 \cdot Trucks + 0.01 \cdot DR5 \\
&\quad - 0.02 \cdot Cost \\
FWD_t &= 0.0732 \cdot FWD_{base} + 1.067 \cdot FWD_{t-1} + 0.0038 \cdot Trucks + 0.0707 \cdot DR5
\end{aligned} \tag{22}
$$

Table 4.19 Three-course HMA overlay with crack and seat of PCC pavement SURE

Dependent variable: IRI t	Coefficient	*t*-stat	P-value
IRI t-1	1.0001	165.6180	0.0000
Trucks (in 100,000s)	0.0595	3.1490	0.0016
Cost 50K	2.1066	2.0760	0.0379
R-square	0.9718		
Adjusted R-square	0.9716		
Dependent variable: PCR t	Coefficient	*t*-stat	P-value
Constant	-1.6127	-2.3680	0.0179
PCR t-1	0.9693	30.4160	0.0000
R-square	0.8013		
Adjusted R-square	0.8004		
Dependent variable: RUT t	Coefficient	*t*-stat	P-value
RUT t-1	1.2711	99.5310	0.0000
DR 2	-0.0012	-1.8310	0.0670
R-square	0.9276		
Adjusted R-square	0.9272		
Dependent variable: FWD t	Coefficient	*t*-stat	P-value
FWD base	0.0460	3.6430	0.0003
FWD t-1	1.0632	70.4200	0.0000
R-square	0.9956		
Adjusted R-square	0.9956		
System's R-square	0.9241		
System's Adjusted R-square	0.9237		
Number of observations	221		

$$\begin{aligned}
IRI_t &= 1.0001 \cdot IRI_{t-1} + 0.0595 \cdot Trucks + 2.1066 \cdot Cost50K \\
PCR_t &= -1.6127 + 0.9693 \cdot PCR_{t-1} \\
RUT_t &= 1.2711 \cdot RUT_{t-1} - 0.0012 \cdot DR2 \\
FWD_t &= 0.046 \cdot FWD_{base} + 1.0632 \cdot FWD_{t-1}
\end{aligned} \tag{23}$$

Table 4.20 3-R and 4-R overlay treatments SURE

Dependent variable: IRI t	Coefficient	*t*-stat	P-value
Constant	0.1480	3.1140	0.0018
IRI t-1	1.0080	64.4630	0.0000
Trucks (in 100,000s)	0.0427	2.0720	0.0383
DR 5	3.5333	2.8190	0.0048
R-square	0.9575		
Adjusted R-square	0.9570		
Dependent variable: PCR t	Coefficient	*t*-stat	P-value
PCR t-1	0.9865	118.7710	0.0000
Trucks (in 100,000s)	-0.0340	-2.7930	0.0052
DR 1	2.0345	2.1230	0.0337
Cost 50K	-1.5569	-2.5710	0.0101
R-square	0.7534		
Adjusted R-square	0.7500		
Dependent variable: RUT t	Coefficient	*t*-stat	P-value
Constant	0.0064	1.6890	0.0912
RUT t-1	1.0382	60.9770	0.0000
Trucks (in 100,000s)	0.0002	3.7490	0.0002
R-square	0.9354		
Adjusted R-square	0.9348		
Dependent variable: FWD t	Coefficient	*t*-stat	P-value
FWD base	-0.1200	-3.7230	0.0002
FWD t-1	1.1986	68.3960	0.0000
Trucks (in 100,000s)	0.0004	2.4630	0.0138
DR 2	-0.1699	-2.5230	0.0116
Cost 50K	0.1654	3.1170	0.0018
R-square	0.9956		
Adjusted R-square	0.9956		
System's R-square	0.9105		
System's Adjusted R-square	0.9093		
Number of observations	221		

$$
\begin{aligned}
IRI_t &= 0.148 + 1.0008 \cdot IRI_{t-1} + 0.0427 \cdot Trucks + 3.5333 \cdot DR5 \\
PCR_t &= 0.9865 \cdot PCR_{t-1} - 0.034 \cdot Trucks + 2.0345 \cdot DR1 \\
&\quad - 1.5569 \cdot Cost50K \\
RUT_t &= 0.0064 + 1.0382 \cdot RUT_{t-1} + 0.0002 \cdot Trucks \\
FWD_t &= -0.12 \cdot FWD_{base} + 1.1986 \cdot FWD_{t-1} + 0.0004 \cdot Trucks \\
&\quad - 0.1699 \cdot DR2 + 0.1654 \cdot Cost50K
\end{aligned}
\tag{24}
$$

Table 4.21 3-R/4-R pavement replacement treatments SURE

Dependent variable: IRI t	Coefficient	*t*-stat	P-value
Constant	1.4698	2.6300	0.0085
IRI base	-0.0983	-1.9590	0.0502
IRI t-1	1.1334	21.1760	0.0000
R-square	0.9788		
Adjusted R-square	0.9786		
Dependent variable: PCR t	Coefficient	*t*-stat	P-value
Constant	-10.3658	-2.6250	0.0087
PCR base	0.1023	2.6230	0.0087
PCR t-1	0.9978	14.4910	0.0000
Trucks (in 100,000s)	-0.0156	-1.7990	0.0721
R-square	0.7037		
Adjusted R-square	0.6995		
Dependent variable: RUT t	Coefficient	*t*-stat	P-value
RUT t-1	1.0544	97.1730	0.0000
Trucks (in 100,000s)	0.0002	2.1700	0.0300
R-square	0.9245		
Adjusted R-square	0.9241		
Dependent variable: FWD t	Coefficient	*t*-stat	P-value
Constant	0.0340	2.9900	0.0028
FWD base	0.0769	6.1680	0.0000
FWD t-1	1.0240	64.6810	0.0000
R-square	0.9974		
Adjusted R-square	0.9974		
System's R-square	0.9011		
System's Adjusted R-square	0.8999		
Number of observations	213		

$$\begin{aligned} IRI_t &= 1.4698 - 0.0983 \cdot IRI_{base} + 1.1334 \cdot IRI_{t-1} \\ PCR_t &= -10.3658 + 0.1023 \cdot PCR_{base} + 0.9978 \cdot PCR_{t-1} - 0.0156 \cdot Trucks \\ RUT_t &= 1.0544 \cdot RUT_{t-1} + 0.0002 \cdot Trucks \\ FWD_t &= 0.034 + 0.0769 \cdot FWD_{base} + 1.024 \cdot FWD_{t-1} \end{aligned} \tag{25}$$

4.3.4. Urban Roads: Interstates

Tables 4.22 through 4.27 and Equations (26) through (31) present the model results for the SURE urban interstate models of the six rehabilitation treatments.

Table 4.22 Two-course HMA overlay with or without surface milling SURE

Dependent variable: IRI t	Coefficient	*t*-stat	P-value
Constant	5.5800	4.7778	0.0000
IRI base	0.0912	3.6090	0.0003
IRI t-1	0.9660	41.8359	0.0000
Trucks (in 100,000s)	0.0157	3.7589	0.0002
DR 5	1.5203	1.8514	0.0641
Cost (in million USD)	-0.9021	-1.7082	0.0876
R-square	0.9401		
Adjusted R-square	0.9394		
Dependent variable: PCR t	Coefficient	*t*-stat	P-value
Constant	-9.7195	-3.1136	0.0018
PCR base	0.0826	2.1024	0.0355
PCR t-1	0.9795	34.0380	0.0000
DR 4	-1.0760	-2.8548	0.0043
R-square	0.8041		
Adjusted R-square	0.8026		
Dependent variable: RUT t	Coefficient	*t*-stat	P-value
RUT t-1	1.2159	28.3915	0.0000
DR 4	0.0344	3.2210	0.0013
R-square	0.6565		
Adjusted R-square	0.6554		
System's R-square	0.8002		
System's Adjusted R-square	0.7992		
Number of observations	415		

$$
\begin{aligned}
IRI_t &= 5.58 + 0.0912 \cdot IRI_{base} + 0.966 \cdot IRI_{t-1} + 0.0157 \cdot Trucks \\
&\quad + 1.5203 \cdot DR5 - 0.9021 \cdot Cost \\
PCR_t &= -9.7195 + 0.0826 \cdot PCR_{base} + 0.9795 \cdot PCR_{t-1} - 1.076 \cdot DR4 \\
RUT_t &= 1.2159 \cdot RUT_{t-1} + 0.0344 \cdot DR4
\end{aligned} \tag{26}
$$

Table 4.23 Concrete pavement restoration SURE

Dependent variable: IRI t	Coefficient	*t*-stat	P-value
Constant	1.5819	2.4030	0.0163
IRI t-1	1.0482	76.5970	0.0000
Trucks (in 100,000s)	0.0380	3.7030	0.0002
Cost (in million USD)	-0.4046	-2.6740	0.0075
R-square	0.9551		
Adjusted R-square	0.9546		
Dependent variable: PCR t	Coefficient	*t*-stat	P-value
Constant	-3.6451	-1.8220	0.0685
PCR t-1	0.9939	28.6660	0.0000
Cost (in million USD)	1.0334	2.1420	0.0322
R-square	0.7691		
Adjusted R-square	0.7672		
Dependent variable: RUT t	Coefficient	*t*-stat	P-value
Constant	0.0112	3.8400	0.0001
RUT t-1	1.1122	56.3810	0.0000
Trucks (in 100,000s)	0.0001	2.3500	0.0188
R-square	0.9215		
Adjusted R-square	0.9209		
System's R-square	0.8819		
System's Adjusted R-square	0.8809		
Number of observations	257		

$$
\begin{aligned}
IRI_t &= 1.5819 + 1.0482 \cdot IRI_{t-1} + 0.038 \cdot Trucks - 0.4046 \cdot Cost \\
PCR_t &= -3.6451 + 0.9939 \cdot PCR_{t-1} + 1.0334 \cdot Cost \\
RUT_t &= 0.0112 + 1.1122 \cdot RUT_{t-1} + 0.0001 \cdot Trucks
\end{aligned} \tag{27}
$$

Table 4.24 Three-course HMA overlay with or without surface milling SURE

Dependent variable: IRI t	Coefficient	*t*-stat	P-value
Constant	7.4400	10.7840	0.0000
IRI t-1	0.9888	67.6470	0.0000
DR 5	3.7937	3.0800	0.0021
Cost 50K	2.0006	2.6500	0.0081
R-square	0.9471		
Adjusted R-square	0.9464		
Dependent variable: PCR t	Coefficient	*t*-stat	P-value
PCR t-1	0.9583	149.6230	0.0000
Trucks (in 100,000s)	-0.0066	-2.1140	0.0345
Cost 50K	-1.5923	-3.3720	0.0007
R-square	0.8122		
Adjusted R-square	0.8107		
Dependent variable: RUT t	Coefficient	*t*-stat	P-value
RUT base	0.1550	4.3490	0.0000
RUT t-1	1.1890	46.7770	0.0000
R-square	0.9346		
Adjusted R-square	0.9343		
Dependent variable: FWD t	Coefficient	*t*-stat	P-value
Constant	0.1405	5.0060	0.0000
FWD base	-0.2281	-9.6130	0.0000
FWD t-1	1.2359	93.6640	0.0000
Cost 50K	0.0561	2.1750	0.0296
R-square	0.9974		
Adjusted R-square	0.9974		
System's R-square	0.9228		
System's Adjusted R-square	0.9222		
Number of observations	252		

$$
\begin{aligned}
IRI_t &= 7.44 + 0.9888 \cdot IRI_{t-1} + 3.7937 \cdot DR5 + 2.0006 \cdot Cost50K \\
PCR_t &= 0.9583 \cdot PCR_{t-1} - 0.0066 \cdot Trucks - 1.5923 \cdot Cost50K \\
RUT_t &= 0.155 \cdot RUT_{base} + 1.189 \cdot RUT_{t-1} \\
FWD_t &= 0.1405 - 0.2281 \cdot FWD_{base} + 1.2359 \cdot FWD_{t-1} + 0.0561 \cdot Cost50K
\end{aligned} \tag{28}
$$

Table 4.25 Three-course HMA overlay with crack and seat of PCC pavement SURE

Dependent variable: IRI t	Coefficient	*t*-stat	P-value
Constant	9.9826	4.7630	0.0000
IRI t-1	0.9978	44.0240	0.0000
DR 3	-2.9958	-1.6910	0.0908
Cost (in million USD)	-1.1682	-1.9380	0.0527
R-square	0.9234		
Adjusted R-square	0.9219		
Dependent variable: PCR t	Coefficient	*t*-stat	P-value
Constant	-1.0140	-52.8030	
PCR t-1	0.9583	196.4790	0.0000
DR 3	1.0770	1.8880	0.0590
Cost 50K	-1.6614	-3.1940	0.0014
R-square	0.8948		
Adjusted R-square	0.8934		
Dependent variable: RUT t	Coefficient	*t*-stat	P-value
Constant	0.0148	3.1130	0.0018
RUT base	0.0988	2.0560	0.0398
RUT t-1	1.1175	31.6230	0.0000
Trucks (in 100,000s)	0.0001	2.8430	0.0045
DR 2	-0.0085	-1.8460	0.0649
Cost 50K	0.0071	1.8720	0.0612
R-square	0.9312		
Adjusted R-square	0.9289		
Dependent variable: FWD t	Coefficient	*t*-stat	P-value
FWD base	-0.0722	-1.8760	0.0607
FWD t-1	1.1353	53.4520	0.0000
R-square	0.9950		
Adjusted R-square	0.9949		
System's R-square	0.9361		
System's Adjusted R-square	0.9348		
Number of observations	155		

$$\begin{aligned}
IRI_t &= 9.9826 + 0.9978 \cdot IRI_{t-1} - 2.9958 \cdot DR3 - 1.1682 \cdot Cost \\
PCR_t &= -1.014 + 0.9583 \cdot PCR_{t-1} + 1.077 \cdot DR3 - 1.6614 \cdot Cost50K \\
RUT_t &= 0.0148 + 0.0988 \cdot RUT_{base} + 1.1175 \cdot RUT_{t-1} + 0.0001 \cdot Trucks \\
&\quad - 0.0085 \cdot DR2 + 0.0071 \cdot Cost50K \\
FWD_t &= -0.0722 \cdot FWD_{base} + 1.1353 \cdot FWD_{t-1}
\end{aligned} \tag{29}$$

Table 4.26 3-R and 4-R overlay treatments SURE

Dependent variable: IRI t	Coefficient	*t*-stat	P-value
Constant	5.8678	4.0020	0.0001
IRI t-1	0.9936	40.0450	0.0000
Trucks (in 100,000s)	0.0218	1.7550	0.0793
DR 3	-4.2240	-2.5600	0.0105
Cost 50K	4.6399	2.7370	0.0062
R-square	0.8795		
Adjusted R-square	0.8766		
Dependent variable: PCR t	Coefficient	*t*-stat	P-value
Constant	-4.4796	-2.9360	0.0033
PCR t-1	1.0448	26.5260	0.0000
Trucks (in 100,000s)	-0.0086	-1.9540	0.0507
DR 5	-1.2757	-2.0000	0.0455
R-square	0.7713		
Adjusted R-square	0.7672		
Dependent variable: RUT t	Coefficient	*t*-stat	P-value
Constant	0.0270	5.0580	0.0000
RUT t-1	1.0767	32.4320	0.0000
Trucks (in 100,000s)	0.0001	2.2900	0.0220
DR 2	-0.0079	-1.8330	0.0668
Cost 50K	0.0141	3.3510	0.0008
R-square	0.8417		
Adjusted R-square	0.8380		
Dependent variable: FWD t	Coefficient	*t*-stat	P-value
Constant	0.2852	5.9100	0.0000
FWD base	-0.1468	-4.7300	0.0000
FWD t-1	1.1331	69.3200	0.0000
R-square	0.9978		
Adjusted R-square	0.9978		
System's R-square	0.8726		
System's Adjusted R-square	0.8699		
Number of observations	174		

$$
\begin{aligned}
IRI_t &= 5.8678 + 0.9936 \cdot IRI_{t-1} + 0.0218 \cdot Trucks - 4.224 \cdot DR3 \\
&\quad + 4.6399 \cdot Cost50K \\
PCR_t &= -4.4796 + 1.0448 \cdot PCR_{t-1} - 0.0086 \cdot Trucks - 1.2757 \cdot DR5 \\
RUT_t &= 0.027 + 1.0767 \cdot RUT_{t-1} + 0.0001 \cdot Trucks - 0.0079 \cdot DR2 \\
&\quad + 0.0141 \cdot Cost50K \\
FWD_t &= 0.2852 - 0.1468 \cdot FWD_{base} + 1.1331 \cdot FWD_{t-1}
\end{aligned} \tag{30}
$$

Table 4.27 3-R/4-R pavement replacement treatments SURE

Dependent variable: IRI t	Coefficient	*t* -stat	P-value
Constant	8.6285	10.3810	0.0000
IRI t-1	0.9888	77.3990	0.0000
DR 5	1.3487	1.8290	0.0674
R-square	0.9494		
Adjusted R-square	0.9491		
Dependent variable: PCR t	Coefficient	*t* -stat	P-value
PCR base	-0.0331	-3.7880	0.0002
PCR t-1	0.9961	28.7370	0.0000
R-square	0.7966		
Adjusted R-square	0.7960		
Dependent variable: RUT t	Coefficient	*t* -stat	P-value
Constant	0.0221	6.6010	0.0000
RUT t-1	1.1215	47.6280	0.0000
DR 5	0.0061	2.1600	0.0308
Cost (in million USD)	-0.0065	-2.8800	0.0040
R-square	0.8826		
Adjusted R-square	0.8814		
Dependent variable: FWD t	Coefficient	*t* -stat	P-value
Constant	0.2182	6.0650	0.0000
FWD base	-0.1047	-5.6960	0.0000
FWD t-1	1.1138	139.0070	0.0000
R-square	0.9917		
Adjusted R-square	0.9917		
System's R-square	0.9051		
System's Adjusted R-square	0.9045		
Number of observations	308		

$$
\begin{aligned}
IRI_t &= 8.6285 + 0.9888 \cdot IRI_{t-1} + 1.3487 \cdot DR5 \\
PCR_t &= -0.0331 \cdot PCR_{base} + 0.9961 \cdot PCR_{t-1} \\
RUT_t &= 0.0221 + 1.1215 \cdot RUT_{t-1} + 0.0061 \cdot DR5 - 0.0065 \cdot Cost \\
FWD_t &= 0.2182 - 0.1047 \cdot FWD_{base} + 1.1138 \cdot FWD_{t-1}
\end{aligned} \tag{31}
$$

4.3.5. Urban Roads: Non-Interstates NHS

Tables 4.28 through 4.33 and Equations (32) through (37) present the model results for the SURE urban non-interstate of the NHS models of the six rehabilitation treatments.

Table 4.28 Two-course HMA overlay with or without surface milling SURE

Dependent variable: IRI t	Coefficient	*t*-stat	P-value
Constant	2.4459	3.1850	0.0014
IRI t-1	1.0104	109.1350	0.0000
Trucks (in 100,000s)	0.0713	2.5710	0.0102
Cost (in million USD)	-0.9658	-1.7700	0.0767
R-square	0.9554		
Adjusted R-square	0.9551		
Dependent variable: PCR t	Coefficient	*t*-stat	P-value
Constant	-9.9257	-5.4140	0.0000
PCR t-1	1.0668	49.4130	0.0000
R-square	0.8210		
Adjusted R-square	0.8207		
Dependent variable: RUT t	Coefficient	*t*-stat	P-value
Constant	0.0328	5.8400	0.0000
RUT base	-0.1288	-3.5380	0.0004
RUT t-1	1.1072	26.1990	0.0000
DR 5	-0.0091	-2.8830	0.0039
Cost (in million USD)	-0.0025	-2.2110	0.0271
R-square	0.9351		
Adjusted R-square	0.9346		
System's R-square	0.9038		
System's Adjusted R-square	0.9035		
Number of observations	529		

$$
\begin{aligned}
IRI_t &= 2.4459 + 1.0104 \cdot IRI_{t-1} + 0.0713 \cdot Trucks - 0.9658 \cdot Cost \\
PCR_t &= -9.9257 + 1.0668 \cdot PCR_{t-1} \\
RUT_t &= 0.0328 - 0.1288 \cdot RUT_{base} + 1.1072 \cdot RUT_{t-1} - 0.0091 \cdot DR5 \\
&\quad - 0.0025 \cdot Cost
\end{aligned}
\tag{32}
$$

Table 4.29 Concrete pavement restoration SURE

Dependent variable: IRI t	Coefficient	*t* -stat	P-value
Constant	5.4022	3.8140	0.0001
IRI t-1	1.0567	81.9010	0.0000
R-square	0.9605		
Adjusted R-square	0.9603		
Dependent variable: PCR t	Coefficient	*t* -stat	P-value
Constant	-1.0115	-4.0940	0.0000
PCR t-1	1.0000	30.1140	0.0000
Trucks (in 100,000s)	-0.0286	-1.8060	0.0708
R-square	0.7917		
Adjusted R-square	0.7901		
Dependent variable: RUT t	Coefficient	*t* -stat	P-value
Constant	0.0128	7.0590	0.0000
RUT base	-0.1588	-11.6876	0.0000
RUT t-1	1.1972	40.3075	0.0000
DR 5	-0.0091	-4.7853	0.0000
Cost (in million USD)	-0.0025	-4.0379	0.0000
R-square	0.9231		
Adjusted R-square	0.9225		
System's R-square	0.8918		
System's Adjusted R-square	0.8910		
Number of observations	251		

$$
\begin{aligned}
& IRI_t = 5.4022 + 1.0567 \cdot IRI_{t-1} \\
& PCR_t = -1.0115 + 0.9999 \cdot PCR_{t-1} - 0.0286 \cdot Trucks \\
& RUT_t = 0.0128 - 0.1588 \cdot RUT_{base} + 1.1972 \cdot RUT_{t-1} - 0.0091 \cdot DR5 \\
& - 0.0025 \cdot Cost
\end{aligned} \quad (33)
$$

Table 4.30 Three-course HMA overlay with or without surface milling SURE

Dependent variable: IRI t	Coefficient	*t*-stat	P-value
IRI base	-0.0155	-2.1410	0.0323
IRI t-1	1.0009	12.5330	0.0000
Trucks (in 100,000s)	0.1040	2.4070	0.0161
Cost 50K	9.2062	4.5090	0.0000
R-square	0.9237		
Adjusted R-square	0.9225		
Dependent variable: PCR t	Coefficient	*t*-stat	P-value
Constant	-6.1876	-2.1960	0.0281
PCR t-1	1.0267	27.5420	0.0000
R-square	0.8010		
Adjusted R-square	0.7999		
Dependent variable: RUT t	Coefficient	*t*-stat	P-value
RUT base	0.0068	2.7170	0.0066
RUT t-1	1.0011	16.6370	0.0000
Trucks (in 100,000s)	0.0003	3.0990	0.0019
DR 3	-0.0061	-1.9320	0.0534
Cost 50K	0.0159	4.1310	0.0000
R-square	0.9093		
Adjusted R-square	0.9073		
Dependent variable: FWD t	Coefficient	*t*-stat	P-value
Constant	0.2833	2.8590	0.0043
FWD base	0.0983	6.7140	0.0000
FWD t-1	1.0293	69.2150	0.0000
Cost (in million USD)	-0.1610	-1.6650	0.0959
R-square	0.9969		
Adjusted R-square	0.9969		
System's R-square	0.9077		
System's Adjusted R-square	0.9066		
Number of observations	187		

$$\begin{aligned}
IRI_t &= -0.0155 \cdot IRI_{base} + 1.0009 \cdot IRI_{t-1} + 0.104 \cdot Trucks + 9.2062 \cdot Cost50K \\
PCR_t &= -6.1876 + 1.0267 \cdot PCR_{t-1} \\
RUT_t &= 0.0068 \cdot RUT_{base} + 1.0011 \cdot RUT_{t-1} + 0.0003 \cdot Trucks - 0.0061 \cdot Dr3 \\
&\quad + 0.0159 \cdot Cost50K \\
FWD_t &= 0.2833 + 0.0983 \cdot FWD_{base} + 1.0293 \cdot FWD_{t-1} - 0.161 \cdot Cost
\end{aligned} \tag{34}$$

Table 4.31 Three-course HMA overlay with crack and seat of PCC pavement SURE

Dependent variable: IRI t	Coefficient	*t*-stat	P-value
Constant	1.5051	1.6890	0.0913
IRI t-1	1.0088	87.3220	0.0000
Trucks (in 100,000s)	0.0459	1.8870	0.0592
R-square	0.9392		
Adjusted R-square	0.9389		
Dependent variable: PCR t	Coefficient	*t*-stat	P-value
Constant	-5.7965	-4.0280	0.0001
PCR t-1	1.0242	45.0710	0.0000
DR 5	-1.0010	-1.9580	0.0502
Cost (in million USD)	0.2429	2.5330	0.0113
R-square	0.8506		
Adjusted R-square	0.8494		
Dependent variable: RUT t	Coefficient	*t*-stat	P-value
RUT t-1	1.0020	105.4350	0.0000
Trucks (in 100,000s)	0.0003	3.5270	0.0004
DR 3	-0.0050	-2.7090	0.0067
R-square	0.9267		
Adjusted R-square	0.9263		
Dependent variable: FWD t	Coefficient	*t*-stat	P-value
FWD base	0.0118	4.2940	0.0000
FWD t-1	1.0011	65.3390	0.0000
Trucks (in 100,000s)	0.0064	2.3810	0.0173
R-square	0.9891		
Adjusted R-square	0.9890		
System's R-square	0.9264		
System's Adjusted R-square	0.9259		
Number of observations	370		

$$
\begin{aligned}
IRI_t &= 1.5051 + 1.0088 \cdot IRI_{t-1} + 0.0459 \cdot Trucks \\
PCR_t &= -5.7965 + 1.0242 \cdot PCR_{t-1} - 1.001 \cdot DR5 + 0.2429 \cdot Cost \\
RUT_t &= 1.002 \cdot RUT_{t-1} + 0.0003 \cdot Trucks - 0.005 \cdot DR3 \\
&\quad - 0.0085 \cdot DR2 + 0.0071 \cdot Cost50K \\
FWD_t &= 0.0118 \cdot FWD_{base} + 1.0011 \cdot FWD_{t-1} + 0.0064 \cdot Trucks
\end{aligned} \tag{35}
$$

Table 4.32 3-R and 4-R overlay treatments SURE

Dependent variable: IRI t	Coefficient	*t*-stat	P-value
IRI base	0.1507	5.7190	0.0000
IRI t-1	1.0005	16.2160	0.0000
DR 5	13.3838	7.8500	0.0000
Cost 50K	5.1077	3.3190	0.0009
R-square	0.8815		
Adjusted R-square	0.8800		
Dependent variable: PCR t	Coefficient	*t*-stat	P-value
Constant	-14.1994	-2.9350	0.0033
PCR base	0.1223	4.5790	0.0000
PCR t-1	0.9815	20.4430	0.0000
DR 5	-1.5274	-2.6760	0.0075
Cost 50K	-0.9248	-1.7130	0.0868
R-square	0.7579		
Adjusted R-square	0.7537		
Dependent variable: RUT t	Coefficient	*t*-stat	P-value
Constant	0.0118	3.1600	0.0016
RUT base	0.2967	5.0320	0.0000
RUT t-1	1.0975	14.6250	0.0000
DR 5	0.0197	5.6040	0.0000
Cost 50K	0.0165	5.0050	0.0000
R-square	0.8946		
Adjusted R-square	0.8946		
Dependent variable: FWD t	Coefficient	*t*-stat	P-value
Constant	0.2096	3.0800	0.0021
FWD base	0.0928	9.4553	0.0000
FWD t-1	1.0198	28.0785	0.0000
R-square	0.9957		
Adjusted R-square	0.9956		
System's R-square	0.8824		
System's Adjusted R-square	0.8810		
Number of observations	231		

$$
\begin{aligned}
IRI_t &= 0.1507 \cdot IRI_{base} + 1.0005 \cdot IRI_{t-1} + 13.3838 \cdot DR5 + 5.1077 \cdot Cost50K \\
PCR_t &= -14.1994 + 0.1223 \cdot PCR_{base} + 0.9815 \cdot PCR_{t-1} - 1.5274 \cdot DR5 \\
&\quad - 0.9248 \cdot Cost50K \\
RUT_t &= 0.0118 + 0.2967 \cdot RUT_{base} + 1.0975 \cdot RUT_{t-1} + 0.0197 \cdot DR5 \\
&\quad + 0.0165 \cdot Cost50K \\
FWD_t &= 0.2096 + 0.0928 \cdot FWD_{base} + 1.0198 \cdot FWD_{t-1}
\end{aligned}
\tag{36}
$$

Table 4.33 3-R/4-R pavement replacement treatments SURE

Dependent variable: IRI t	Coefficient	*t*-stat	P-value
Constant	8.4556	2.1600	0.0308
IRI t-1	1.0010	12.8150	0.0000
R-square	0.7048		
Adjusted R-square	0.6998		
Dependent variable: PCR t	Coefficient	*t*-stat	P-value
Constant	-28.7657	-5.3620	0.0000
PCR base	0.3523	5.5340	0.0000
PCR t-1	0.8792	20.9960	0.0000
DR 5	-2.0658	-3.4610	0.0005
Cost 50K	-2.3933	-4.4250	0.0000
R-square	0.8451		
Adjusted R-square	0.8416		
Dependent variable: RUT t	Coefficient	*t*-stat	P-value
RUT base	0.0086	5.5110	0.0000
RUT t-1	1.0074	10.9930	0.0000
Trucks (in 100,000s)	0.0003	3.3750	0.0007
DR 5	0.0196	4.0650	0.0000
Cost 50K	0.0156	3.4720	0.0005
R-square	0.8881		
Adjusted R-square	0.8855		
Dependent variable: FWD t	Coefficient	*t*-stat	P-value
Constant	0.0629	3.2060	0.0013
FWD base	-0.1166	-2.8430	0.0045
FWD t-1	1.1177	55.3370	0.0000
R-square	0.9952		
Adjusted R-square	0.9952		
System's R-square	0.8583		
System's Adjusted R-square	0.8555		
Number of observations	180		

$$\begin{aligned}
IRI_t &= 8.4556 + 1.001 \cdot IRI_{t-1} \\
PCR_t &= -28.7657 + 0.3523 \cdot PCR_{base} + 0.8792 \cdot PCR_{t-1} - 2.0658 \cdot DR5 \\
&\quad - 2.3933 \cdot Cost50K \\
RUT_t &= 0.0086 \cdot RUT_{base} + 1.0074 \cdot RUT_{t-1} + 0.0003 \cdot Trucks + 0.0196 \cdot DR5 \\
&\quad + 0.0156 \cdot Cost50K \\
FWD_t &= 0.0629 - 0.1166 \cdot FWD_{base} + 1.1177 \cdot FWD_{t-1}
\end{aligned} \tag{37}$$

4.3.6. Urban Roads: Non-Interstates Non-NHS

Tables 4.34 through 4.39 and Equations (38) through (43) present the model results for the SURE urban non-interstate non-NHS models of the six rehabilitation treatments.

Table 4.34 Two-course HMA overlay with or without surface milling SURE

Dependent variable: IRI t	Coefficient	*t*-stat	P-value
IRI t-1	1.0646	257.8020	0.0000
Trucks (in 100,000s)	0.0492	1.8290	0.0674
R-square	0.9561		
Adjusted R-square	0.9561		
Dependent variable: PCR t	Coefficient	*t*-stat	P-value
PCR base	-0.0895	-2.5950	0.0095
PCR t-1	1.0458	28.8910	0.0000
DR 5	0.8950	1.8390	0.0659
Cost (in million USD)	0.5313	1.6990	0.0893
R-square	0.7309		
Adjusted R-square	0.7297		
Dependent variable: RUT t	Coefficient	*t*-stat	P-value
Constant	0.0458	7.3550	0.0000
RUT t-1	1.0476	95.6150	0.0000
Trucks (in 100,000s)	0.0001	1.8030	0.0714
Cost (in million USD)	-0.0043	-2.3740	0.0176
R-square	0.9174		
Adjusted R-square	0.9171		
System's R-square	0.8682		
System's Adjusted R-square	0.8676		
Number of observations	708		

$$\begin{aligned} IRI_t &= 1.0646 \cdot IRI_{t-1} + 0.0492 \cdot Trucks \\ PCR_t &= -0.0895 \cdot PCR_{base} + 1.0458 \cdot PCR_{t-1} + 0.895 \cdot DR5 + 0.5313 \cdot Cost \\ RUT_t &= 0.0458 + 1.0476 \cdot RUT_{t-1} + 0.0001 \cdot Trucks - 0.0043 \cdot Cost \end{aligned} \tag{38}$$

Table 4.35 Concrete pavement restoration SURE

Dependent variable: IRI t	Coefficient	*t* -stat	P-value
Constant	3.7788	4.7690	0.0000
IRI t-1	1.0235	221.6430	0.0000
Trucks (in 100,000s)	0.0425	1.7970	0.0724
R-square	0.9866		
Adjusted R-square	0.9866		
Dependent variable: PCR t	Coefficient	*t* -stat	P-value
Constant	-6.8967	-4.0000	0.0001
PCR t-1	1.0250	50.0430	0.0000
Cost (in million USD)	0.6624	1.8300	0.0672
R-square	0.8007		
Adjusted R-square	0.8000		
Dependent variable: RUT t	Coefficient	*t* -stat	P-value
Constant	0.0425	5.4610	0.0000
RUT base	0.1780	2.9240	0.0035
RUT t-1	1.0091	15.1760	0.0000
R-square	0.9260		
Adjusted R-square	0.9258		
System's R-square	0.9044		
System's Adjusted R-square	0.9041		
Number of observations	593		

$$
\begin{aligned}
IRI_t &= 3.7788 + 1.0235 \cdot IRI_{t-1} + 0.0425 \cdot Trucks \\
PCR_t &= -6.8967 + 1.025 \cdot PCR_{t-1} + 0.6624 \cdot Cost \\
RUT_t &= 0.0425 + 0.178 \cdot RUT_{base} + 1.0091 \cdot RUT_{t-1}
\end{aligned} \tag{39}
$$

Table 4.36 Three-course HMA overlay with or without surface milling SURE

Dependent variable: IRI t	Coefficient	*t*-stat	P-value
Constant	7.5319	4.4210	0.0000
IRI t-1	1.0369	100.2390	0.0000
DR 3	-1.0075	-3.3230	0.0009
R-square	0.9787		
Adjusted R-square	0.9785		
Dependent variable: PCR t	Coefficient	*t*-stat	P-value
PCR t-1	0.9745	222.4540	0.0000
Trucks (in 100,000s)	-0.0178	-2.6150	0.0089
R-square	0.7372		
Adjusted R-square	0.7359		
Dependent variable: RUT t	Coefficient	*t*-stat	P-value
RUT t-1	1.0831	97.3200	0.0000
Trucks (in 100,000s)	0.0002	1.9690	0.0490
R-square	0.9233		
Adjusted R-square	0.9230		
Dependent variable: FWD t	Coefficient	*t*-stat	P-value
Constant	0.4893	4.0300	0.0001
FWD base	-0.1916	-5.4850	0.0000
FWD t-1	1.1736	64.2680	0.0000
DR 2	-0.1045	-1.9820	0.0475
R-square	0.9960		
Adjusted R-square	0.9960		
System's R-square	0.9088		
System's Adjusted R-square	0.9083		
Number of observations	205		

$$
\begin{aligned}
IRI_t &= 7.5319 + 1.0369 \cdot IRI_{t-1} - 1.0075 \cdot DR3 \\
PCR_t &= 0.9745 \cdot PCR_{t-1} - 0.0178 \cdot Trucks \\
RUT_t &= 1.0831 \cdot RUT_{t-1} + 0.0002 \cdot Trucks \\
FWD_t &= 0.4893 - 0.1916 \cdot FWD_{base} + 1.1736 \cdot FWD_{t-1} - 0.1045 \cdot DR2
\end{aligned}
\tag{40}
$$

Table 4.37 Three-course HMA overlay with crack and seat of PCC pavement SURE

Dependent variable: IRI t	Coefficient	*t*-stat	P-value
IRI t-1	1.0156	127.0600	0.0000
Trucks (in 100,000s)	0.0612	1.7740	0.0761
DR 5	4.7833	1.6950	0.0902
Cost (in million USD)	-2.5948	-2.3450	0.0190
R-square	0.9563		
Adjusted R-square	0.9557		
Dependent variable: PCR t	Coefficient	*t*-stat	P-value
Constant	-7.1822	-2.5280	0.0115
PCR t-1	1.0412	25.7470	0.0000
R-square	0.7446		
Adjusted R-square	0.7434		
Dependent variable: RUT t	Coefficient	*t*-stat	P-value
Constant	0.0294	6.1190	0.0000
RUT base	0.0853	1.7790	0.0753
RUT t-1	1.0492	19.0060	0.0000
R-square	0.9606		
Adjusted R-square	0.9602		
Dependent variable: FWD t	Coefficient	*t*-stat	P-value
Constant	0.3815	6.2250	0.0000
FWD base	-0.1893	-7.4350	0.0000
FWD t-1	1.1719	85.3990	0.0000
R-square	0.9979		
Adjusted R-square	0.9978		
System's R-square	0.9148		
System's Adjusted R-square	0.9143		
Number of observations	210		

$$
\begin{aligned}
IRI_t &= 1.0156 \cdot IRI_{t-1} + 0.0612 \cdot Trucks + 4.7833 \cdot DR5 - 2.5948 \cdot Cost \\
PCR_t &= -7.1822 + 1.0412 \cdot PCR_{t-1} \\
RUT_t &= 0.0294 + 0.0853 \cdot RUT_{base} + 1.0492 \cdot RUT_{t-1} \\
FWD_t &= 0.3815 - 0.1893 \cdot FWD_{base} + 1.1719 \cdot FWD_{t-1}
\end{aligned}
\tag{41}
$$

Table 4.38 3-R and 4-R overlay treatments SURE

Dependent variable: IRI t	Coefficient	*t*-stat	P-value
IRI t-1	1.0166	191.2310	0.0000
Trucks (in 100,000s)	0.0548	1.7350	0.0828
Cost (in million USD)	-2.7055	-2.7730	0.0056
R-square	0.9744		
Adjusted R-square	0.9741		
Dependent variable: PCR t	Coefficient	*t*-stat	P-value
PCR t-1	0.9932	156.0580	0.0000
Trucks (in 100,000s)	-0.0255	-1.6780	0.0934
Cost 50K	-1.3460	-2.2290	0.0258
R-square	0.7391		
Adjusted R-square	0.7361		
Dependent variable: RUT t	Coefficient	*t*-stat	P-value
Constant	0.0360	2.6740	0.0075
RUT t-1	1.0800	38.9970	0.0000
DR 3	-0.0098	-2.0830	0.0372
R-square	0.8984		
Adjusted R-square	0.8967		
Dependent variable: FWD t	Coefficient	*t*-stat	P-value
FWD t-1	1.0422	416.0170	0.0000
Trucks (in 100,000s)	0.0021	1.8720	0.0612
R-square	0.9974		
Adjusted R-square	0.9974		
System's R-square	0.9023		
System's Adjusted R-square	0.9011		
Number of observations	177		

$$
\begin{aligned}
IRI_t &= 1.0166 \cdot IRI_{t-1} + 0.0548 \cdot Trucks - 2.7055 \cdot Cost \\
PCR_t &= 0.9932 \cdot PCR_{t-1} - 0.0255 \cdot Trucks - 1.346 \cdot Cost50K \\
RUT_t &= 0.036 + 1.08 \cdot RUT_{t-1} - 0.0098 \cdot DR3 \\
FWD_t &= 1.0422 \cdot FWD_{t-1} + 0.0021 \cdot Trucks
\end{aligned}
\qquad (42)
$$

Table 4.39 3-R/4-R pavement replacement treatments SURE

Dependent variable: IRI t	Coefficient	*t* -stat	P-value
Constant	1.3122	4.0600	0.0000
IRI base	-0.0092	-7.6820	0.0000
IRI t-1	1.0162	14.4110	0.0000
DR 3	-5.4621	-4.8470	0.0000
Trucks (in 100,000s)	0.0814	5.1320	0.0000
Cost 50K	6.1630	4.5340	0.0000
R-square	0.9321		
Adjusted R-square	0.9308		
Dependent variable: PCR t	Coefficient	*t* -stat	P-value
Constant	-7.8286	-2.6780	0.0074
PCR base	0.0679	3.0290	0.0025
PCR t-1	0.9590	22.3150	0.0000
DR 5	-1.5921	-3.1070	0.0019
Cost (in million USD)	1.7937	2.2710	0.0232
R-square	0.7544		
Adjusted R-square	0.7505		
Dependent variable: RUT t	Coefficient	*t* -stat	P-value
Constant	0.0089	3.0450	0.0023
RUT base	0.0274	5.1400	0.0000
RUT t-1	1.0006	15.8500	0.0000
Trucks (in 100,000s)	0.0003	3.0360	0.0024
DR 3	-0.0077	-2.3350	0.0195
Cost 50K	0.0173	5.0390	0.0000
R-square	0.8907		
Adjusted R-square	0.8885		
Dependent variable: FWD t	Coefficient	*t* -stat	P-value
Constant	0.2343	4.2690	0.0000
FWD base	-0.1481	-4.0750	0.0000
FWD t-1	1.1487	62.7530	0.0000
DR 5	0.1374	2.1880	0.0286
Cost 50K	0.1273	2.3300	0.0198
R-square	0.9945		
Adjusted R-square	0.9944		
System's R-square	0.8929		
System's Adjusted R-square	0.8911		
Number of observations	259		

$$
\begin{aligned}
IRI_t &= 1.3122 - 0.0092 \cdot IRI_{base} + 1.0162 \cdot IRI_{t-1} - 5.4621 \cdot DR3 \\
&\quad + 0.0814 \cdot Trucks + 6.163 \cdot Cost50K \\
PCR_t &= -7.8286 + 0.0679 \cdot PCR_{base} + 0.959 \cdot PCR_{t-1} - 1.5921 \cdot DR5 \\
&\quad - 1.7937 \cdot Cost \\
RUT_t &= 0.0089 + 0.0274 \cdot RUT_{base} + 1.0006 \cdot RUT_{t-1} + 0.0003 \cdot Trucks \\
&\quad - 0.0077 \cdot DR3 + 0.0173 \cdot Cost50K \\
FWD_t &= 0.2343 - 0.1481 \cdot FWD_{base} + 1.1487 \cdot FWD_{t-1} + 0.1374 \cdot DR5 \\
&\quad + 0.1273 \cdot Cost50K
\end{aligned} \tag{43}
$$

4.4. Discussion of the Model Results

Some general findings from the SURE models are summarized below.

- Effect of the pavement condition in the base year: The IRI, PCR, rut depth and surface deflection measurements taken the year right after the rehabilitation are all found to play a strong role in the determination of the corresponding pavement condition in many of the models. Their effect (i.e., positive or negative sign, and magnitude), however, depends on the other significant variables of each corresponding model.

- Effect of the pavement condition in the preceding year (t-1) of the forecasting year (t) of analysis: These lag variables (i.e., IRI, PCR, rut depth and surface deflection measurements taken the year, t-1, before the analysis year, t) are highly significant in all the models. In most cases, (provided that all other parameters are set to be zero) the lag variable for the IRI has a value greater than one, indicating that the IRI in year t will be slightly higher than the IRI in the preceding year (t-1)[31]. The lag for the PCR has a value less than one, indicating

[31] Note that as the IRI increases, the smoothness of the pavement decreases. Hence, this indicates that the pavement condition with respect to the IRI in periods t and t-1 deteriorates over time.

that the PCR in period t will be lower than the PCR in the preceding period[32]. The lag for rut depth has a value greater than one, indicating that the rut depth in period t will be slightly higher than the rut depth in period t-1. And, finally, the lag for surface deflection also has a value greater than one, indicating that the deflection of the surface in period t will be slightly higher than the one in period t-1.

- Effect of trucks: The cumulative daily number of commercial trucks over the treatment study period is an important influential factor for the determination (and deterioration) of the pavement condition. The effect of trucks is very significant in most of the models: as the number of trucks increases (or decreases), the IRI, rut depth and surface deflection increase (or decrease), whereas the PCR decreases (or increases). (For specifics on the effect of truck loads on the pavement performance see Mannering et al., 2009.)

- Effect of drainage: Although drainage of water from pavements is an important consideration in road construction, modern processing and placement of materials sometimes result in base courses that do not transmit water or drain. This, combined with increased truck loads, often leads to pavement distress caused by moisture in the structures. Water is also present in pavement materials in the form of free water, capillary water, bound moisture, or water vapor (NCHRP, 1997). According to NCHRP (1997), the primary source of water in pavements is atmospheric precipitation which can enter the pavement through cracks, infiltration, shoulders and ditches, or high groundwater. It is then moved by gravity, capillary forces, and temperature or pressure differences. As such, inadequate drainage results in faster deterioration of the pavement condition. Going back to the model results, seven drainage classes are considered (excessive, somewhat excessive, good, moderately good, somewhat poor, poor,

---

[32] High values of PCR (the maximum value is 100) indicate an excellent pavement condition, whereas low values indicate a poor condition. Therefore, this means that the pavement condition with respect to PCR deteriorates from period t to period t-1.

and very poor) and five combinations (excessively or somewhat excessively drained; excessively, somewhat excessively, or well drained; excessively, somewhat excessively, well, or moderately well drained; somewhat poorly, poorly, or very poorly drained; and poorly or very poorly drained) are found to significantly influence the pavement condition indicators. Well drained pavements have higher PCR and lower IRI, rut depth and surface deflection measurements, whereas poorly drained pavements have lower PCR and higher IRI, rut depth and surface deflection measurements. Note that a number of weather (temperature, precipitation) and surface geology (soil type such as glacial soils, residual soils, lacustrine soils, etc.) variables were initially considered in the models, but after the inclusion of the drainage variables they all became statistically insignificant. This indicates that the effect of weather and geology on the pavement performance is mostly captured by the drainage variables.

- Effect of the treatment contract final cost per lane-mile: The variables representing the cost per lane-mile of the contract corresponding to the treatment implemented and completed in the base year (the year when the pavement was rehabilitated), are found to play a key role in the pavement performance. The cost variable is found to be significant in most of the models with two forms; as a continuous variable, and as an indicator (dummy) variable representing the road sections where the occurred rehabilitation cost per lane-mile is less than 50,000 USD. Both forms indicate the positive relationship between the cost amount per lane-mile spent for pavement rehabilitation and the pavement condition.

4.5. Pavement Performance Forecasting

The purpose of pavement-performance modeling is to forecast pavement performance over time. This section utilizes the 36 equations (Equations (8) through (43)) that are mathematically formulated from the SURE models, to forecast each of the four pavement condition indicators (i.e., IRI, PCR, rut depth, and surface deflection for the structural treatments) for all of the rehabilitation treatments and road functional classes.

With respect to forecasting the pavement condition in year t using the lag t-1 variables, note that the predicted values for each consecutive year are used to predict the sequential year. For example, assume that the pavement condition in year 2007 (i.e., t-1) is known, and the corresponding values are used to predict the pavement condition in year 2008 (i.e., t). To predict the pavement condition in year 2009 (i.e., t'), the predicted pavement condition in year 2008 (t) becomes the known pavement condition of the preceding year 2008 (i.e., t'-1) and is utilized as an input in the models. Similarly, the predicted values of the pavement condition in year 2009 (t') become an input in the model (i.e., as t''-1) to predict the pavement condition in year 2010 (i.e., t''), and so on.

For the forecasts, the following *a priori* assumptions are made.

All road functional classes:

- Base Year = 2006
- Year of 1st Forecast, t = 2008
- Year before the Forecast Year, t-1 = 2007
- Base IRI = 30 in/mi
- Base PCR = 100
- Base RUT = 0.02 in
- Base FWD = 2 mils (for structural treatments only)
- IRI t-1 = 40 in/mi
- PCR t-1 = 97
- RUT t-1 = 0.05 in
- FWD t-1 = 3 mils (for structural treatments only)
- Drainage class = Well drained
- Prediction horizon = 20 years
- Yearly increase in AADT = 3%

Rural interstates:

- Contract Cost per mile = 350,000 USD
- AADT = 32,000 veh/day
- Percentage of Commercial Trucks = 25%

Rural non-interstates of the NHS:

- Contract Cost per mile = 288,000 USD
- AADT = 10,000 veh/day
- Percentage of Commercial Trucks = 15%

Rural non-interstates non-NHS:

- Contract Cost per mile = 160,000 USD
- AADT = 6,000 veh/day
- Percentage of Commercial Trucks = 11%

Urban interstates:

- Contract Cost per mile = 484,000 USD
- AADT = 26,000 veh/day
- Percentage of Commercial Trucks = 35%

Urban non-interstates of the NHS:

- Contract Cost per mile = 268,000 USD
- AADT = 9,000 veh/day
- Percentage of Commercial Trucks = 18%

Urban non-interstates non-NHS:

- Contract Cost per mile = 107,000 USD
- AADT = 4,000 veh/day
- Percentage of Commercial Trucks = 12%

Note that the assumptions made separately for each road functional class about the contract cost per lane-mile, AADT, and percentage of commercial trucks as part of the AADT, are based on the mean values corresponding to each road functional class. The cost amounts and AADT have been rounded up to the closest thousand, and the percentage of commercial trucks to the closest hundredth.

The cumulative number of commercial trucks, $\overrightarrow{T_{n\delta}}$, of a road section δ for the forecast year n (for example, assume that the first year of forecast n = 2009, the second year of forecast n = 2010, the third year of forecast n = 2011, and so on) can be estimated using the concept of the uniform series compound amount factor (Sinha and Labi, 2007) as follows:

$$\overrightarrow{T_{n\delta}} = 365 \cdot AADT_{\delta} \cdot T_{\delta} \cdot \frac{(1+i_{\delta})^{(n-\beta)} - 1}{i_{\delta}}, \tag{44}$$

where, T_δ the percentage of commercial trucks as part of the $AADT_\delta$ in road section δ, i_δ the yearly increase of the $AADT_\delta$, and β the base year (i.e., the year right after rehabilitation, for example $\beta = 2006$).

4.5.1. Rural Interstate Models: Pavement Condition Forecasting

Using Equations (8) through (13) and the aforementioned assumptions (general assumptions, and assumptions specific to the rural interstate models), the predicted values of the IRI (in/mi), PCR, rut depth (in), and surface deflection or FWD (mils) for the rural interstate models of all the rehabilitation treatments are estimated, and the results are shown in Table 4.40. The prediction horizon is 20 years, and year t-1 is 2007 (the last year with available data); the first forecast year is 2008. Note that the missing values refer to predicted values of IRI greater than 350 in/mi, PCR less than zero (PCR cannot take negative values, or values greater than 100), rut depth greater than 1.5 inches, and surface deflection greater than 27 mils. The pavement condition corresponding to these values is typically too poor for one to come across in practice, hence their respected values are not illustrated.

Figures 4.34 through 4.37 present a graphical representation of these forecasts in time by rehabilitation treatment type, for the IRI, PCR, rut depth (RUT), and surface deflection (FWD), respectively.

Note that, over a twelve-year period (2007-2018), 2C HMA has a forecasted average deterioration in IRI, PCR, and RUT of 96 in/mi, 38, and 0.59 inches, respectively; and C PVM R of 80 in/mi, 43, and 0.41 inches, respectively. 3C HMA has a forecasted average deterioration in IRI, PCR, RUT, and FWD of 57 in/mi, 42, 0.61 inches, and 12.9 mils, respectively; 3C HMA PCC of 75 in/mi, 45, 0.7 inches, and 9 mils, respectively; 3-R & 4-R of 58 in/mi, 47, 0.43 inches, and 8.3 mils, respectively; and 3-R/4-R of 66 in/mi, 38, 0.39 inches, and 5.6 mils, respectively.

Table 4.40 Actual forecast values of the pavement condition for the rural interstates models

2C HMA				C PVM R				3C HMA					3C HMA PCC					3-R & 4-R					3-R/4-R				
Year	IRI	PCR	RUT	Year	IRI	PCR	RUT	Year	IRI	PCR	RUT	FWD	Year	IRI	PCR	RUT	FWD	Year	IRI	PCR	RUT	FWD	Year	IRI	PCR	RUT	FWD
2007	40	97	0.05	2007	40	97	0.05	2007	40	97	0.05	3.0	2007	40	97	0.05	3.0	2007	40	97	0.05	3.0	2007	40	97	0.05	3.0
2008	41	94	0.06	2008	45	93	0.08	2008	44	92	0.07	3.3	2008	44	94	0.08	3.3	2008	43	95	0.07	3.2	2008	43	93	0.08	3.3
2009	44	91	0.08	2009	50	89	0.11	2009	48	87	0.10	3.7	2009	49	91	0.12	3.6	2009	47	93	0.09	3.5	2009	47	88	0.11	3.6
2010	48	88	0.11	2010	55	85	0.14	2010	53	83	0.13	4.2	2010	54	87	0.16	4.0	2010	50	90	0.11	3.9	2010	52	84	0.14	3.9
2011	53	84	0.14	2011	61	81	0.17	2011	58	79	0.17	4.9	2011	59	83	0.21	4.5	2011	55	87	0.14	4.3	2011	56	81	0.17	4.3
2012	59	81	0.18	2012	68	77	0.21	2012	63	75	0.21	5.7	2012	66	79	0.26	5.1	2012	59	83	0.18	4.9	2012	62	77	0.20	4.7
2013	67	78	0.23	2013	75	73	0.25	2013	68	71	0.26	6.6	2013	72	75	0.33	5.8	2013	65	79	0.21	5.5	2013	68	74	0.24	5.2
2014	77	74	0.29	2014	83	69	0.28	2014	73	67	0.32	7.8	2014	80	71	0.40	6.7	2014	70	74	0.26	6.3	2014	74	70	0.27	5.7
2015	88	70	0.36	2015	91	65	0.33	2015	79	64	0.39	9.3	2015	87	67	0.47	7.7	2015	76	69	0.30	7.3	2015	81	67	0.31	6.3
2016	102	67	0.44	2016	100	62	0.37	2016	85	61	0.47	11.1	2016	96	62	0.56	8.9	2016	83	63	0.35	8.4	2016	89	64	0.35	7.0
2017	118	63	0.53	2017	109	58	0.42	2017	91	58	0.56	13.2	2017	105	57	0.65	10.3	2017	90	57	0.41	9.7	2017	97	62	0.40	7.7
2018	136	59	0.64	2018	120	54	0.46	2018	97	55	0.66	15.9	2018	115	52	0.75	12.0	2018	98	50	0.48	11.3	2018	106	59	0.44	8.6
2019	157	55	0.77	2019	131	50	0.52	2019	104	53	0.79	19.1	2019	125	47	0.86	14.0	2019	107	43	0.55	13.2	2019	116	56	0.49	9.5
2020	181	50	0.91	2020	142	46	0.57	2020	110	50	0.93	23.0	2020	136	41	0.97	16.2	2020	116	35	0.63	15.5	2020	126	54	0.54	10.5
2021	208	46	1.07	2021	155	43	0.63	2021	118	48	1.09		2021	147	35	1.10	18.9	2021	125	26	0.71	18.1	2021	137	52	0.59	11.6
2022	238	42	1.26	2022	168	39	0.69	2022	125	46	1.28		2022	160	29	1.23	22.0	2022	136	17	0.80	21.2	2022	149	50	0.64	12.9
2023	273	37	1.46	2023	181	35	0.75	2023	133	44	1.49		2023	173	23	1.37	25.6	2023	147	7	0.91	24.9	2023	161	48	0.70	14.3
2024	311	32		2024	196	31	0.82	2024	141	42			2024	186	17			2024	159		1.01		2024	174	46	0.76	15.8
2025		28		2025	212	27	0.89	2025	149	40			2025	201	10			2025	171		1.13		2025	188	44	0.82	17.5
2026		23		2026	228	24	0.96	2026	157	38			2026	216	3			2026	185		1.26		2026	203	42	0.89	19.3
2027		18		2027	245	20	1.04	2027	166	37			2027	232				2027	199		1.40		2027	219	40	0.96	21.4

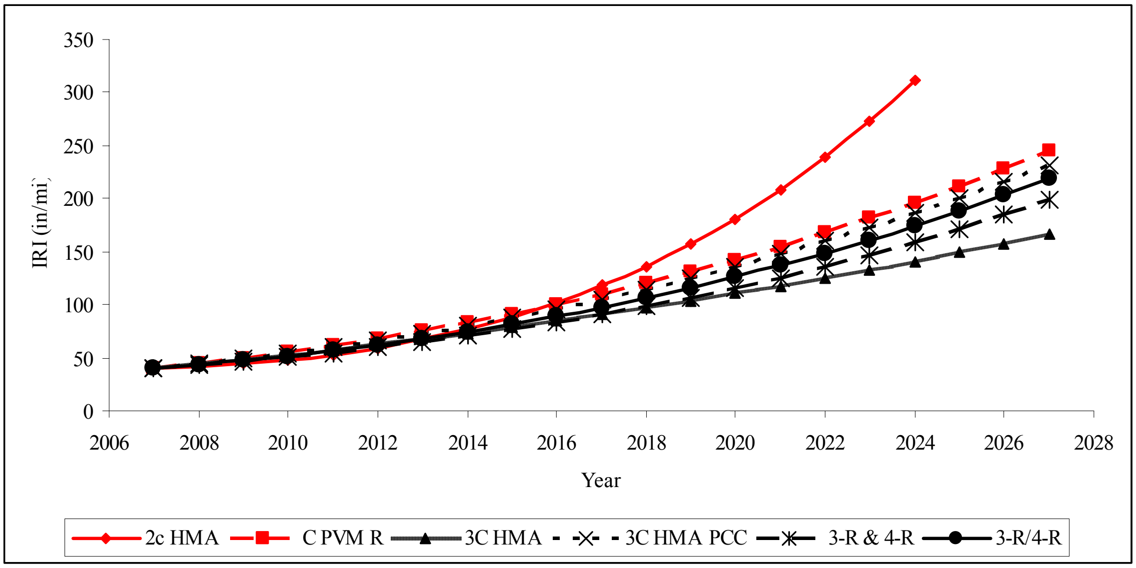

Figure 4.34 IRI forecasts by treatment type for rural interstates

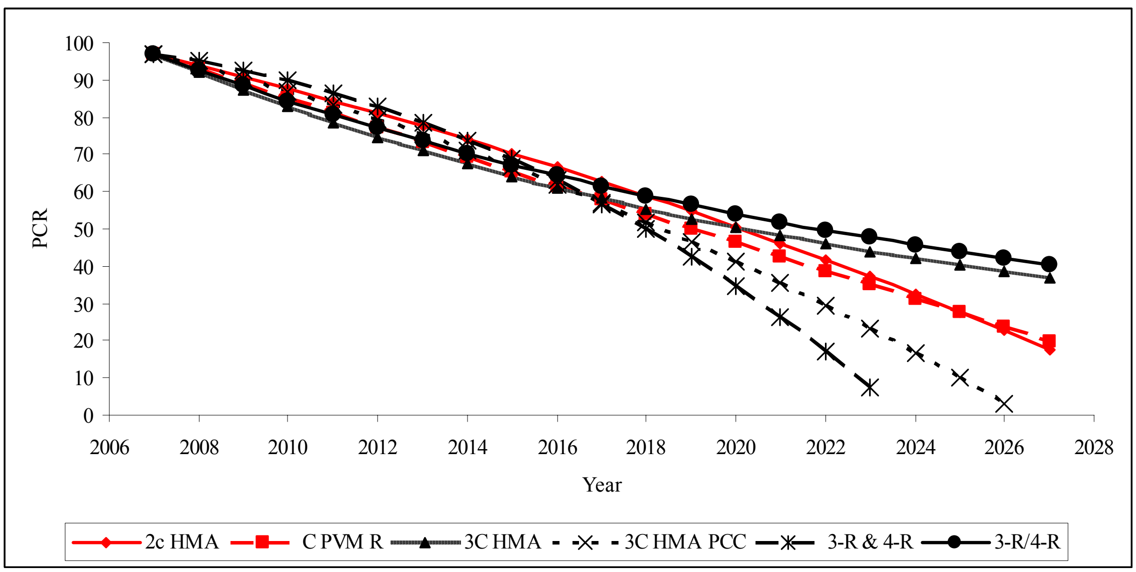

Figure 4.35 PCR forecasts by treatment type for rural interstates

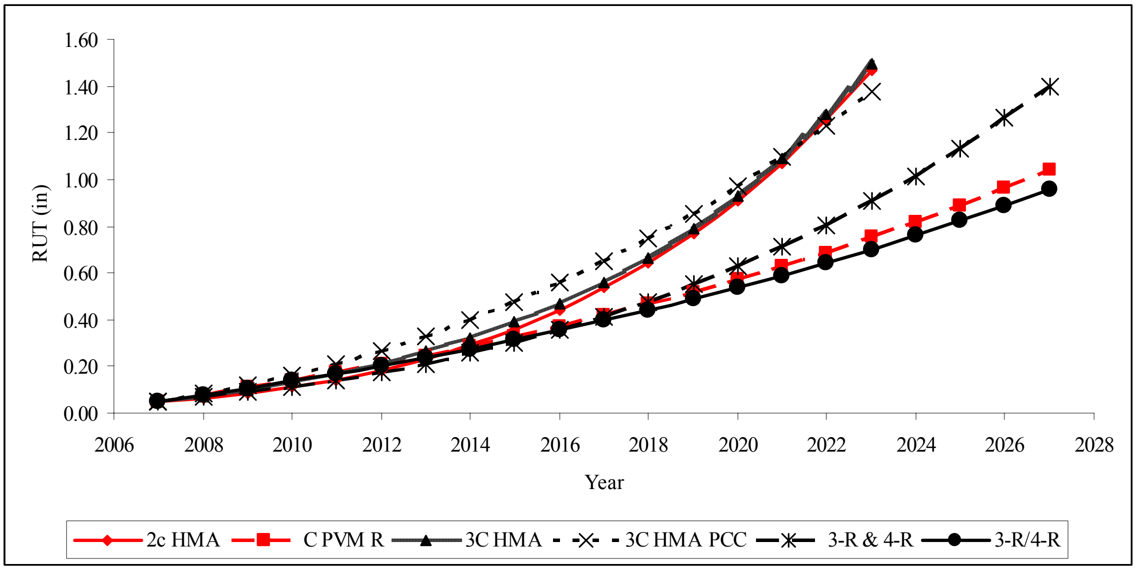

Figure 4.36 RUT forecasts by treatment type for rural interstates

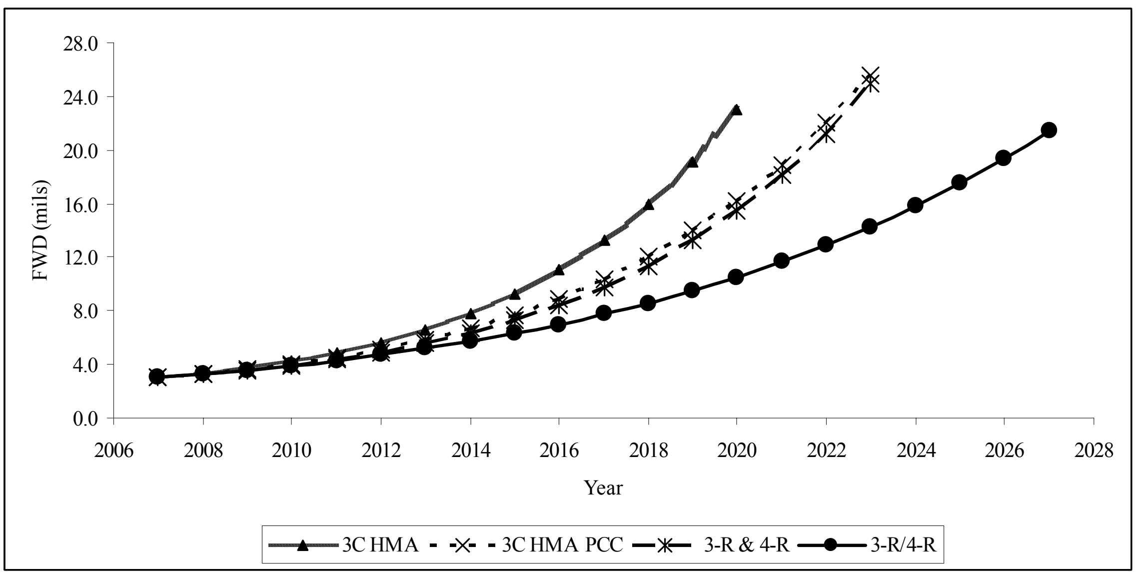

Figure 4.37 FWD forecasts by treatment type for rural interstates

4.5.2. Rural Non-Interstate of the NHS Models: Forecasting the Pavement Condition

Using Equations (14) through (19) and the aforementioned assumptions (general assumptions, and assumptions specific to the rural non-interstates of the NHS models), the predicted values of the IRI (in/mi), PCR, rut depth (in), and surface deflection or FWD (mils) for the rural non-interstates of the NHS models of all the rehabilitation treatments are estimated, and the results are shown in Table 4.41. The prediction horizon is 20 years, and year t-1 is 2007 (the last year with available data); the first forecast year is 2008. As before, note that the missing values refer to predicted values of IRI greater than 350 in/mi, PCR less than zero (PCR cannot take negative values, or values greater than 100), rut depth greater than 1.5 inches, and surface deflection greater than 27 mils; the pavement condition corresponding to these values is typically too poor for one to come across in practice, hence their respected values are not illustrated.

Figures 4.38 through 4.41 present a graphical representation of these forecasts in time by rehabilitation treatment type, for the IRI, PCR, rut depth (RUT), and surface deflection (FWD), respectively.

Note that, over a twelve-year period (2007-2018), 2C HMA has a forecasted average deterioration in IRI, PCR, and RUT of 60 in/mi, 43, and 0.42 inches, respectively; and C PVM R of 39 in/mi, 36, and 0.18 inches, respectively. 3C HMA has a forecasted average deterioration in IRI, PCR, RUT, and FWD of 77 in/mi, 21, 0.27 inches, and 7.4 mils, respectively; 3C HMA PCC of 52 in/mi, 43, 0.29 inches, and 5.6 mils, respectively; 3-R & 4-R of 51 in/mi, 39, 0.22 inches, and 2.4 mils, respectively; and 3-R/4-R of 50 in/mi, 30, 0.16 inches, and 3.1 mils, respectively.

Table 4.41 Actual forecast values of the pavement condition for the rural non-interstates of the NHS models

2C HMA				C PVM R				3C HMA				
Year	IRI	PCR	RUT	Year	IRI	PCR	RUT	Year	IRI	PCR	RUT	FWD
2007	40	97	0.05	2007	40	97	0.05	2007	40	97	0.05	3.0
2008	43	94	0.08	2008	42	94	0.06	2008	47	96	0.06	3.2
2009	47	90	0.11	2009	44	90	0.06	2009	53	95	0.07	3.5
2010	51	86	0.14	2010	46	87	0.07	2010	60	93	0.08	3.8
2011	55	83	0.18	2011	49	84	0.08	2011	67	92	0.10	4.2
2012	60	79	0.21	2012	52	81	0.09	2012	74	91	0.12	4.7
2013	65	75	0.25	2013	56	77	0.11	2013	81	89	0.14	5.3
2014	71	71	0.29	2014	59	74	0.13	2014	88	87	0.17	6.0
2015	78	67	0.33	2015	64	71	0.15	2015	95	85	0.20	6.8
2016	84	63	0.38	2016	68	68	0.17	2016	102	83	0.23	7.8
2017	92	58	0.42	2017	73	64	0.20	2017	109	81	0.28	9.0
2018	100	54	0.47	2018	79	61	0.23	2018	117	78	0.32	10.4
2019	109	50	0.52	2019	85	58	0.27	2019	124	76	0.38	12.1
2020	119	45	0.58	2020	91	54	0.31	2020	132	73	0.44	14.1
2021	130	41	0.63	2021	99	51	0.36	2021	139	70	0.51	16.4
2022	142	36	0.69	2022	106	48	0.41	2022	147	67	0.59	19.2
2023	154	31	0.75	2023	115	45	0.47	2023	155	64	0.68	22.5
2024	168	26	0.82	2024	123	41	0.54	2024	163	60	0.78	26.4
2025	183	21	0.89	2025	133	38	0.62	2025	171	57	0.90	
2026	200	16	0.96	2026	143	35	0.70	2026	179	53	1.03	
2027	217	11	1.03	2027	154	32	0.80	2027	187	49	1.18	

3C HMA PCC					3-R & 4-R					3-R/4-R				
Year	IRI	PCR	RUT	FWD	Year	IRI	PCR	RUT	FWD	Year	IRI	PCR	RUT	FWD
2007	40	97	0.05	3.0	2007	40	97	0.05	3.0	2007	40	97	0.05	3.0
2008	44	92	0.07	3.2	2008	43	93	0.06	3.1	2008	43	95	0.06	3.2
2009	47	88	0.09	3.4	2009	47	89	0.07	3.2	2009	47	92	0.06	3.4
2010	51	84	0.11	3.7	2010	51	86	0.08	3.4	2010	51	90	0.07	3.6
2011	55	80	0.14	4.0	2011	55	82	0.10	3.5	2011	55	87	0.08	3.9
2012	60	76	0.16	4.4	2012	59	78	0.11	3.7	2012	59	84	0.09	4.1
2013	65	72	0.19	4.8	2013	64	75	0.13	3.9	2013	63	82	0.10	4.4
2014	70	68	0.21	5.4	2014	69	71	0.15	4.2	2014	68	79	0.12	4.7
2015	75	64	0.24	6.0	2015	74	68	0.18	4.4	2015	73	76	0.13	5.0
2016	80	61	0.27	6.7	2016	79	64	0.20	4.7	2016	78	73	0.15	5.4
2017	86	57	0.30	7.6	2017	85	61	0.23	5.1	2017	84	70	0.17	5.7
2018	92	54	0.34	8.6	2018	91	58	0.27	5.4	2018	90	67	0.19	6.1
2019	98	51	0.37	9.8	2019	97	54	0.30	5.8	2019	96	64	0.21	6.6
2020	105	48	0.41	11.2	2020	104	51	0.34	6.2	2020	103	61	0.24	7.0
2021	112	45	0.45	12.7	2021	111	48	0.38	6.7	2021	110	58	0.26	7.5
2022	119	42	0.48	14.5	2022	118	45	0.43	7.2	2022	117	55	0.29	8.0
2023	127	39	0.53	16.6	2023	125	42	0.49	7.8	2023	125	51	0.33	8.6
2024	135	37	0.57	19.0	2024	133	39	0.54	8.4	2024	134	48	0.37	9.2
2025	143	34	0.61	21.7	2025	142	36	0.61	9.0	2025	142	45	0.41	9.8
2026	152	32	0.66	24.8	2026	151	33	0.68	9.7	2026	152	41	0.45	10.5
2027	161	29	0.71		2027	160	30	0.75	10.5	2027	162	37	0.50	11.3

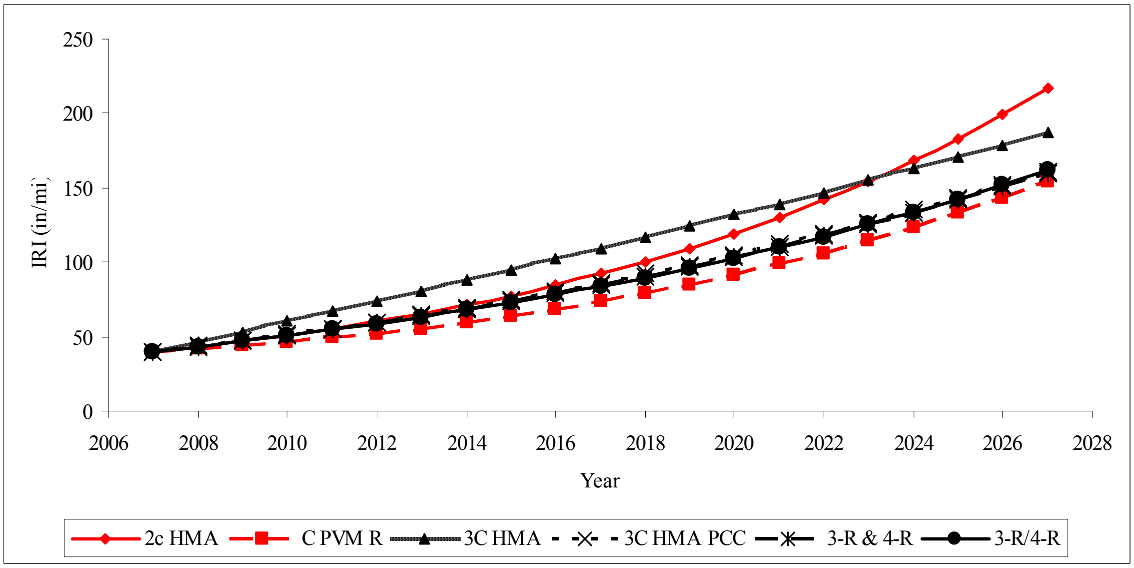

Figure 4.38 IRI forecasts by treatment type for rural non-interstates of the NHS

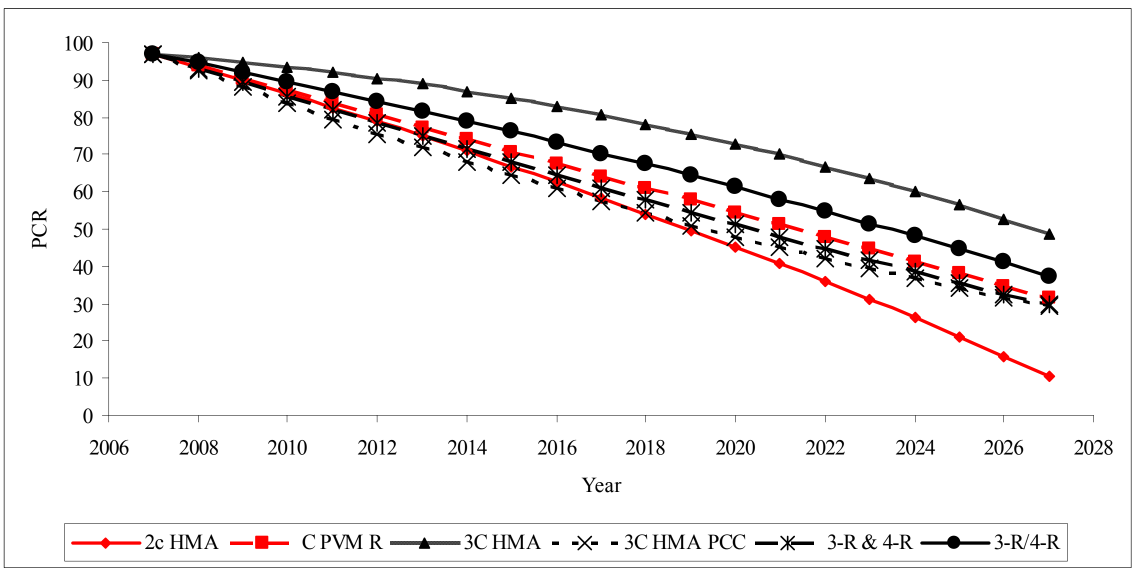

Figure 4.39 PCR forecasts by treatment type for rural non-interstates of the NHS

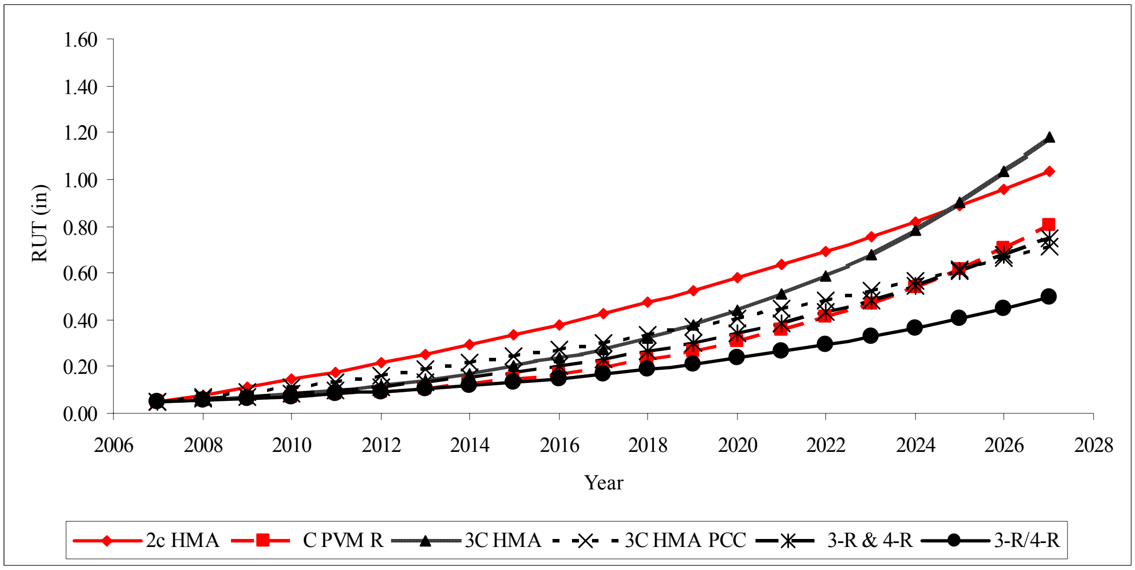

Figure 4.40 RUT forecasts by treatment type for rural non-interstates of the NHS

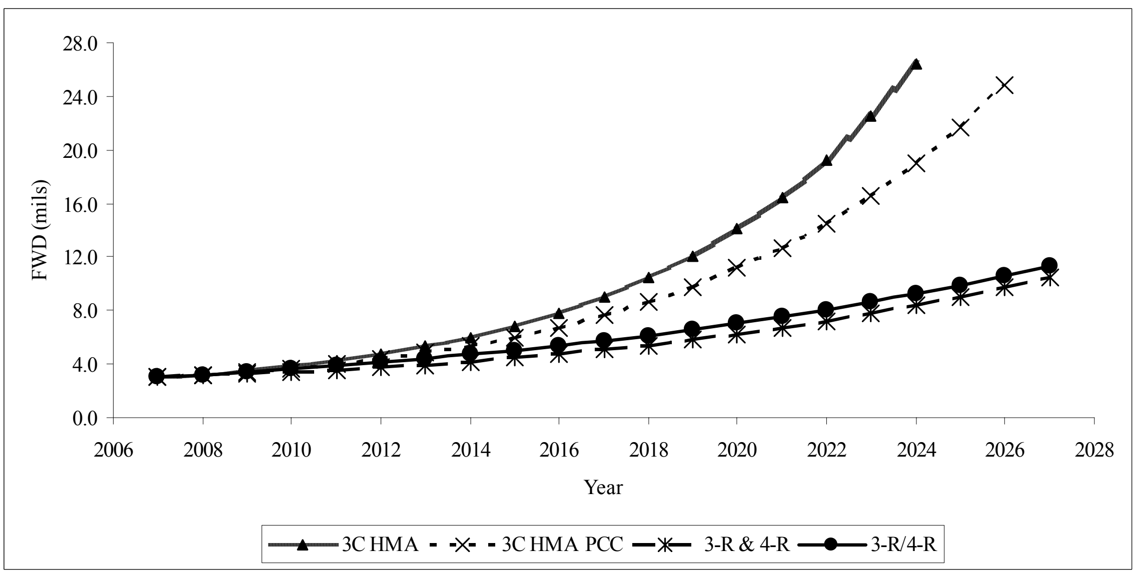

Figure 4.41 FWD forecasts by treatment type for rural non-interstates of the NHS

4.5.3. Rural Non-Interstate Non-NHS Models: Forecasting the Pavement Condition

Using Equations (20) through (25) and the aforementioned assumptions (general assumptions, and assumptions specific to the rural non-interstates non-NHS models), the predicted values of the IRI (in/mi), PCR, rut depth (in), and surface deflection or FWD (mils) for the rural non-interstates non-NHS models of all the rehabilitation treatments are estimated, and the results are shown in Table 4.42. The prediction horizon is 20 years, and year t-1 is 2007 (the last year with available data); the first forecast year is 2008. As before, note that the missing values refer to predicted values of IRI greater than 350 in/mi, PCR less than zero (PCR cannot take negative values, or values greater than 100), rut depth greater than 1.5 inches, and surface deflection greater than 27 mils; the pavement condition corresponding to these values is typically too poor for one to come across in practice, hence their respected values are not illustrated.

Figures 4.42 through 4.45 present a graphical representation of these forecasts in time by rehabilitation treatment type, for the IRI, PCR, rut depth (RUT), and surface deflection (FWD), respectively.

Note that, over a twelve-year period (2007-2018), 2C HMA has a forecasted average deterioration in IRI, PCR, and RUT of 56 in/mi, 46, and 0.14 inches, respectively; and C PVM R of 25 in/mi, 45, and 0.7 inches, respectively. 3C HMA has a forecasted average deterioration in IRI, PCR, RUT, and FWD of 13 in/mi, 11, 0.49 inches, and 6.4 mils, respectively; 3C HMA PCC of 12 in/mi, 47, 0.59 inches, and 4.3 mils, respectively; 3-R & 4-R of 14 in/mi, 20, 0.15 inches, and 6.1 mils, respectively; and 3-R/4-R of 32 in/mi, 40, 0.56 inches, and 7 mils, respectively.

Table 4.42 Actual forecast values of the pavement condition for the rural non-interstates non-NHS models

2C HMA				C PVM R				3C HMA					3C HMA PCC					3-R & 4-R					3-R/4-R				
Year	IRI	PCR	RUT	Year	IRI	PCR	RUT	Year	IRI	PCR	RUT	FWD	Year	IRI	PCR	RUT	FWD	Year	IRI	PCR	RUT	FWD	Year	IRI	PCR	RUT	FWD
2007	40	97	0.05	2007	40	97	0.05	2007	40	97	0.05	3.0	2007	40	97	0.05	3.0	2007	40	97	0.05	3.0	2007	40	97	0.05	3.0
2008	44	92	0.06	2008	42	93	0.07	2008	40	96	0.08	3.4	2008	40	92	0.06	3.3	2008	41	96	0.06	3.2	2008	43	93	0.08	3.4
2009	49	87	0.07	2009	44	88	0.09	2009	41	96	0.11	3.8	2009	41	88	0.08	3.6	2009	41	94	0.07	3.4	2009	46	90	0.11	3.7
2010	53	82	0.08	2010	46	84	0.11	2010	41	95	0.15	4.2	2010	41	84	0.10	3.9	2010	42	92	0.08	3.7	2010	49	86	0.14	4.2
2011	58	78	0.09	2011	48	80	0.14	2011	42	94	0.19	4.7	2011	42	79	0.12	4.2	2011	43	91	0.09	4.0	2011	52	82	0.18	4.7
2012	63	73	0.10	2012	50	76	0.18	2012	43	93	0.23	5.2	2012	43	75	0.16	4.6	2012	45	89	0.10	4.4	2012	55	79	0.22	5.2
2013	68	69	0.11	2013	52	71	0.23	2013	44	92	0.27	5.8	2013	44	71	0.20	5.0	2013	46	87	0.12	4.9	2013	58	75	0.27	5.8
2014	73	65	0.13	2014	55	68	0.30	2014	45	91	0.32	6.4	2014	45	68	0.25	5.4	2014	47	85	0.13	5.4	2014	61	71	0.32	6.5
2015	79	61	0.14	2015	57	64	0.38	2015	47	90	0.37	7.0	2015	47	64	0.31	5.8	2015	49	83	0.15	6.1	2015	63	68	0.39	7.2
2016	84	58	0.16	2016	60	60	0.47	2016	49	89	0.42	7.8	2016	49	60	0.40	6.3	2016	51	81	0.16	6.9	2016	66	64	0.45	8.0
2017	90	54	0.17	2017	62	56	0.60	2017	51	88	0.48	8.5	2017	50	57	0.51	6.8	2017	52	79	0.18	7.9	2017	69	61	0.53	9.0
2018	96	51	0.19	2018	65	52	0.75	2018	53	86	0.54	9.4	2018	52	54	0.64	7.3	2018	54	77	0.20	9.1	2018	72	57	0.61	10.0
2019	102	48	0.21	2019	68	49	0.95	2019	56	85	0.60	10.3	2019	55	50	0.81	7.8	2019	57	74	0.22	10.5	2019	74	54	0.71	11.1
2020	109	45	0.22	2020	71	45	1.19	2020	58	83	0.67	11.3	2020	57	47	1.03	8.4	2020	59	72	0.24	12.2	2020	77	50	0.82	12.4
2021	116	42	0.24	2021	74	42	1.49	2021	62	82	0.74	12.4	2021	60	44	1.31	9.1	2021	62	70	0.26	14.2	2021	80	47	0.94	13.8
2022	123	39	0.26	2022	78	39		2022	65	80	0.81	13.5	2022	63	41		9.7	2022	64	67	0.29	16.7	2022	82	43	1.07	15.4
2023	130	36	0.29	2023	81	35		2023	69	79	0.89	14.8	2023	66	38		10.4	2023	67	64	0.31	19.6	2023	85	40	1.22	17.2
2024	138	34	0.31	2024	85	32		2024	72	77	0.98	16.1	2024	69	35		11.2	2024	70	61	0.34	23.1	2024	88	36	1.39	19.1
2025	145	32	0.33	2025	88	29		2025	77	75	1.07	17.6	2025	73	33		12.0	2025	74	59	0.37		2025	90	33		21.3
2026	153	29	0.36	2026	92	26		2026	81	73	1.17	19.1	2026	77	30		12.8	2026	77	56	0.40		2026	93	29		23.8
2027	162	27	0.38	2027	96	23		2027	86	71	1.27	20.8	2027	81	28		13.7	2027	81	52	0.43		2027	95	26		26.5

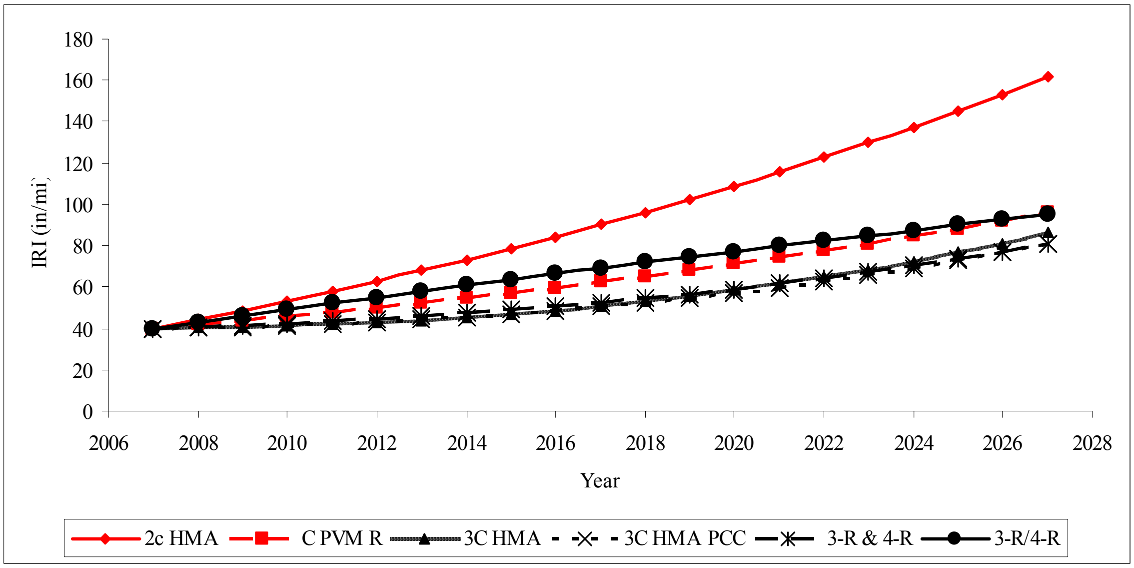

Figure 4.42 IRI forecasts by treatment type for rural non-interstates non-NHS

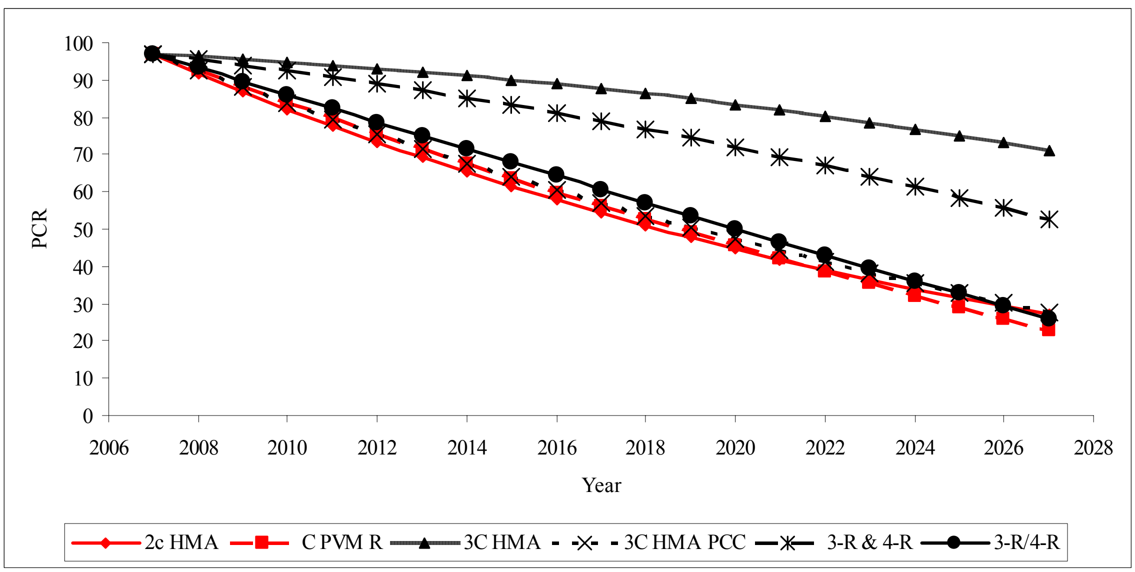

Figure 4.43 PCR forecasts by treatment type for rural non-interstates non-NHS

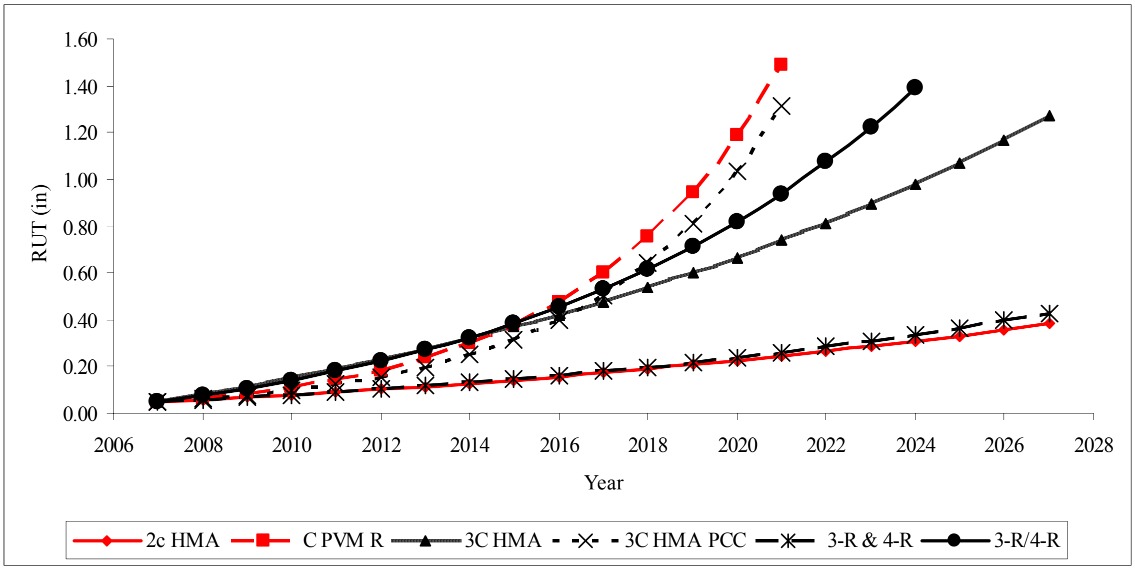

Figure 4.44 RUT forecasts by treatment type for rural non-interstates non-NHS

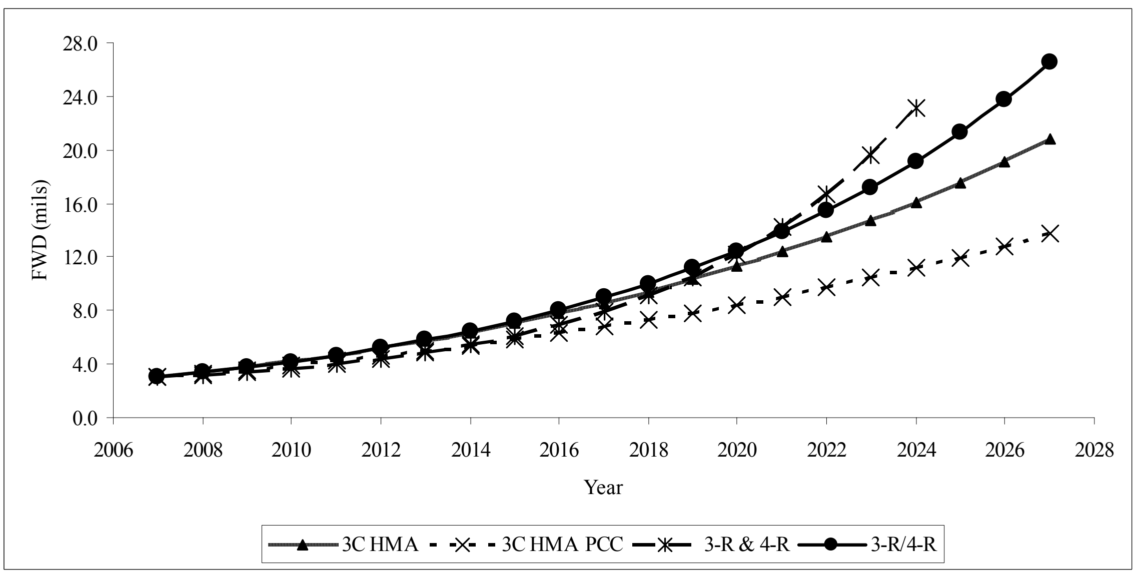

Figure 4.45 FWD forecasts by treatment type for rural non-interstates non-NHS

4.5.4. Urban Interstate Models: Forecasting the Pavement Condition

Using Equations (26) through (31) and the aforementioned assumptions (general assumptions, and assumptions specific to the urban interstate models), the predicted values of the IRI (in/mi), PCR, rut depth (in), and surface deflection or FWD (mils) for the urban interstate models of all the rehabilitation treatments are estimated, and the results are shown in Table 4.43. The prediction horizon is 20 years, and year t-1 is 2007 (the last year with available data); the first forecast year is 2008. As before, note that the missing values refer to predicted values of IRI greater than 350 in/mi, PCR less than zero (PCR cannot take negative values, or values greater than 100), rut depth greater than 1.5 inches, and surface deflection greater than 27 mils; the pavement condition corresponding to these values is typically too poor for one to come across in practice, hence their respected values are not illustrated.

Figures 4.46 through 4.49 present a graphical representation of these forecasts in time by rehabilitation treatment type, for the IRI, PCR, rut depth (RUT), and surface deflection (FWD), respectively.

Note that, over a twelve-year period (2007-2018), 2C HMA has a forecasted average deterioration in IRI, PCR, and RUT of 101 in/mi, 34, and 0.38 inches, respectively; and C PVM R of 176 in/mi, 40, and 0.52 inches, respectively. 3C HMA has a forecasted average deterioration in IRI, PCR, RUT, and FWD of 73 in/mi, 53, 0.38 inches, and 15.4 mils, respectively; 3C HMA PCC of 69 in/mi, 36, 0.44 inches, and 5.9 mils, respectively; 3-R & 4-R of 76 in/mi, 31, 0.42 inches, and 8.7 mils, respectively; and 3-R/4-R of 85 in/mi, 40, 0.52 inches, and 7 mils, respectively.

Table 4.43 Actual forecast values of the pavement condition for the urban interstates models

2C HMA				C PVM R				3C HMA					3C HMA PCC					3-R & 4-R					3-R/4-R				
Year	IRI	PCR	RUT	Year	IRI	PCR	RUT	Year	IRI	PCR	RUT	FWD	Year	IRI	PCR	RUT	FWD	Year	IRI	PCR	RUT	FWD	Year	IRI	PCR	RUT	FWD
2007	40	97	0.05	2007	40	97	0.05	2007	40	97	0.05	3.0	2007	40	97	0.05	3.0	2007	40	97	0.05	3.0	2007	40	97	0.05	3.0
2008	48	94	0.06	2008	46	93	0.07	2008	47	93	0.06	3.4	2008	46	93	0.07	3.3	2008	43	96	0.07	3.4	2008	48	93	0.08	3.4
2009	55	90	0.07	2009	53	90	0.09	2009	54	88	0.08	3.9	2009	53	89	0.09	3.6	2009	46	95	0.10	3.8	2009	56	90	0.10	3.7
2010	64	87	0.09	2010	63	86	0.12	2010	61	83	0.10	4.5	2010	59	86	0.11	3.9	2010	51	94	0.13	4.3	2010	64	86	0.13	4.2
2011	72	84	0.11	2011	74	82	0.15	2011	67	79	0.12	5.2	2011	65	82	0.14	4.3	2011	56	92	0.16	4.9	2011	72	82	0.17	4.7
2012	81	80	0.13	2012	87	79	0.19	2012	74	74	0.14	6.1	2012	72	79	0.17	4.7	2012	62	90	0.19	5.5	2012	80	79	0.21	5.2
2013	90	77	0.16	2013	102	75	0.24	2013	81	69	0.17	7.3	2013	78	75	0.20	5.2	2013	69	87	0.23	6.3	2013	88	75	0.25	5.8
2014	100	74	0.20	2014	120	71	0.29	2014	87	64	0.21	8.7	2014	84	72	0.25	5.8	2014	76	84	0.27	7.1	2014	95	71	0.30	6.5
2015	109	71	0.24	2015	140	68	0.34	2015	94	60	0.25	10.4	2015	90	69	0.30	6.4	2015	85	80	0.32	8.0	2015	103	68	0.36	7.2
2016	119	68	0.29	2016	162	64	0.41	2016	100	55	0.30	12.5	2016	97	67	0.35	7.1	2016	94	76	0.36	9.1	2016	110	64	0.42	8.0
2017	130	66	0.35	2017	187	61	0.49	2017	106	50	0.36	15.2	2017	103	64	0.42	7.9	2017	105	72	0.42	10.3	2017	118	61	0.49	9.0
2018	141	63	0.43	2018	216	57	0.57	2018	113	44	0.43	18.4	2018	109	61	0.49	8.9	2018	116	66	0.47	11.7	2018	125	57	0.57	10.0
2019	152	60	0.52	2019	247	54	0.67	2019	119	39	0.51	22.4	2019	115	59	0.57	9.9	2019	128	60	0.54	13.2	2019	132	54	0.66	11.1
2020	164	57	0.63	2020	282	50	0.78	2020	125	34	0.61		2020	121	56	0.67	11.1	2020	141	54	0.60	15.0	2020	140	50	0.76	12.4
2021	176	55	0.77	2021	320	47	0.91	2021	131	28	0.73		2021	127	54	0.78	12.5	2021	155	46	0.68	16.9	2021	147	47	0.87	13.8
2022	188	52	0.94	2022		43	1.05	2022	137	23	0.87		2022	134	52	0.90	14.0	2022	171	38	0.76	19.2	2022	154	43	0.99	15.4
2023	201	50	1.14	2023		40	1.21	2023	143	17	1.04		2023	140	50	1.04	15.8	2023	187	29	0.84	21.7	2023	160	40	1.13	17.2
2024	214	47	1.39	2024		36	1.39	2024	149	11	1.24		2024	146	48	1.20	17.8	2024	204	19	0.94	24.6	2024	167	36	1.29	19.1
2025	228	45		2025		33		2025	155	5	1.48		2025	152	46	1.37	20.0	2025	223	8	1.04		2025	174	33	1.47	21.3
2026	242	42		2026		30		2026	160				2026	158	44		22.6	2026	243		1.15		2026	181	29		23.8
2027	257	40		2027		26		2027	166				2027	164	42		25.5	2027	263		1.27		2027	187	26		26.5

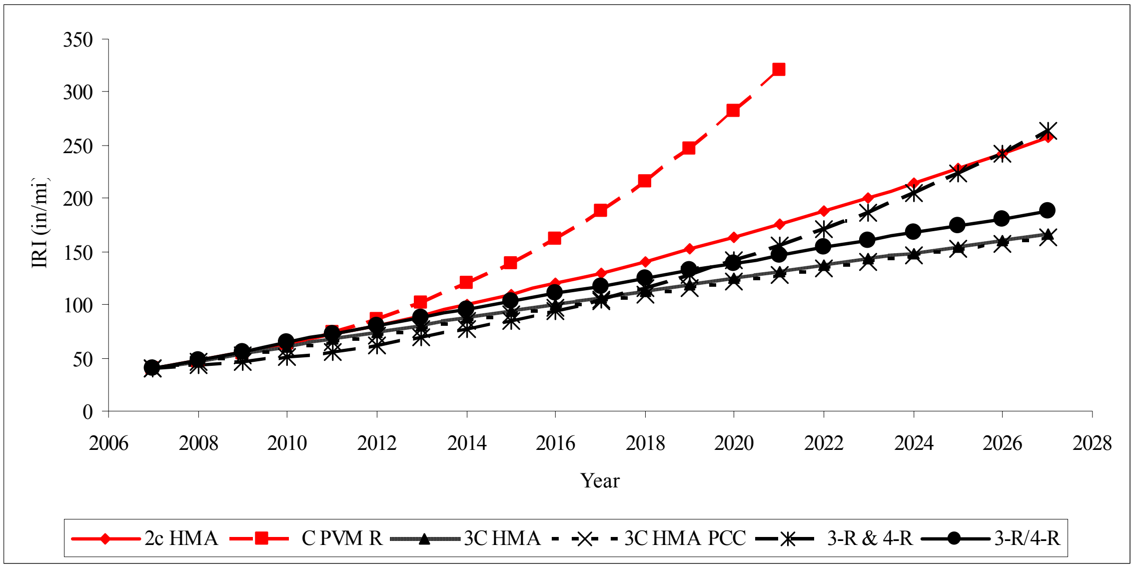

Figure 4.46 IRI forecasts by treatment type for urban interstates

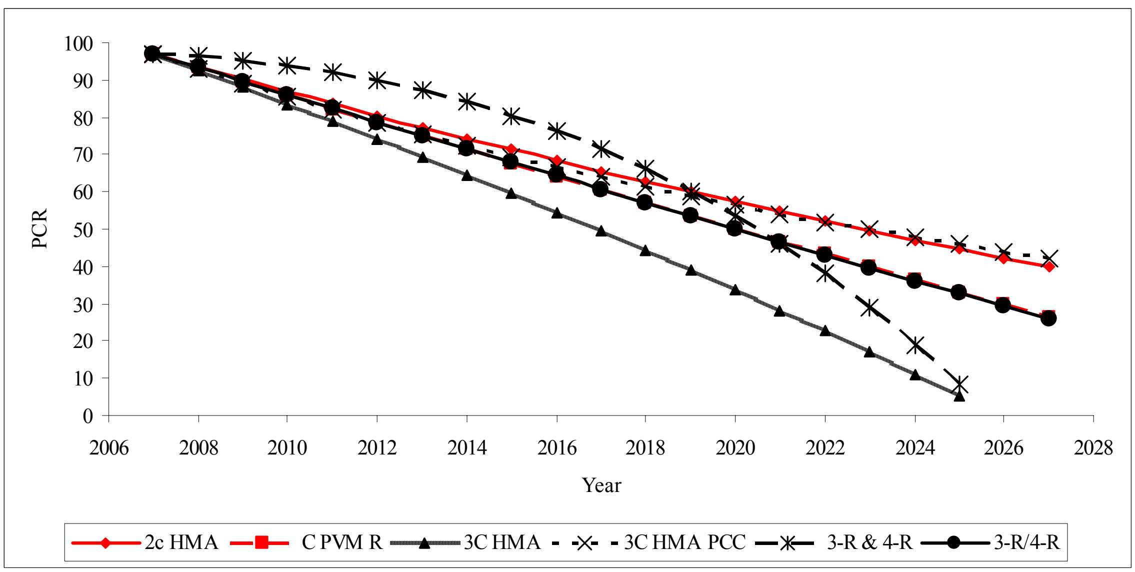

Figure 4.47 PCR forecasts by treatment type for urban interstates

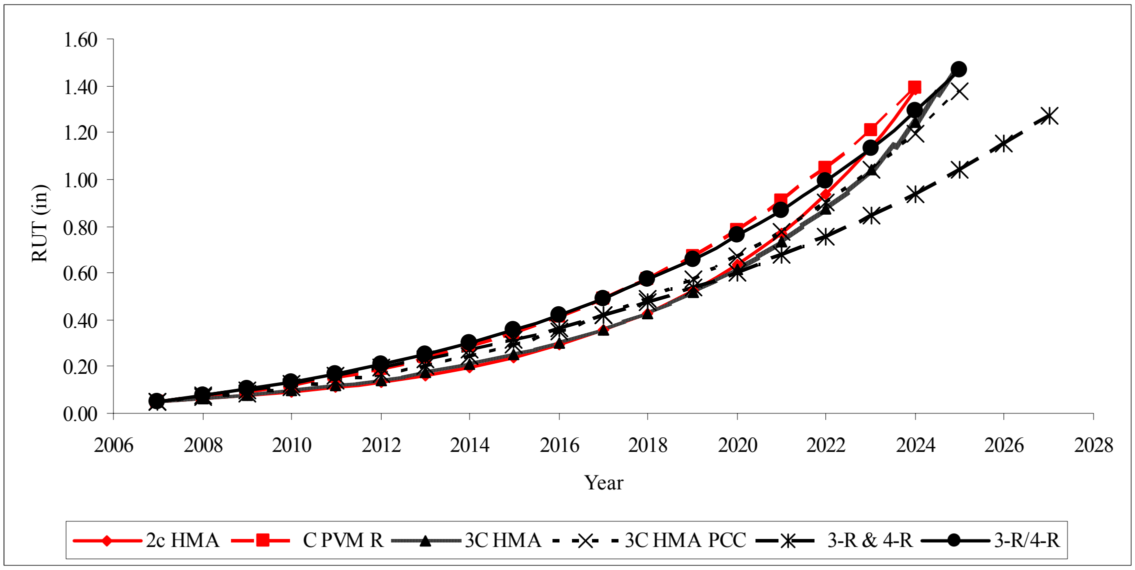

Figure 4.48 RUT forecasts by treatment type for urban interstates

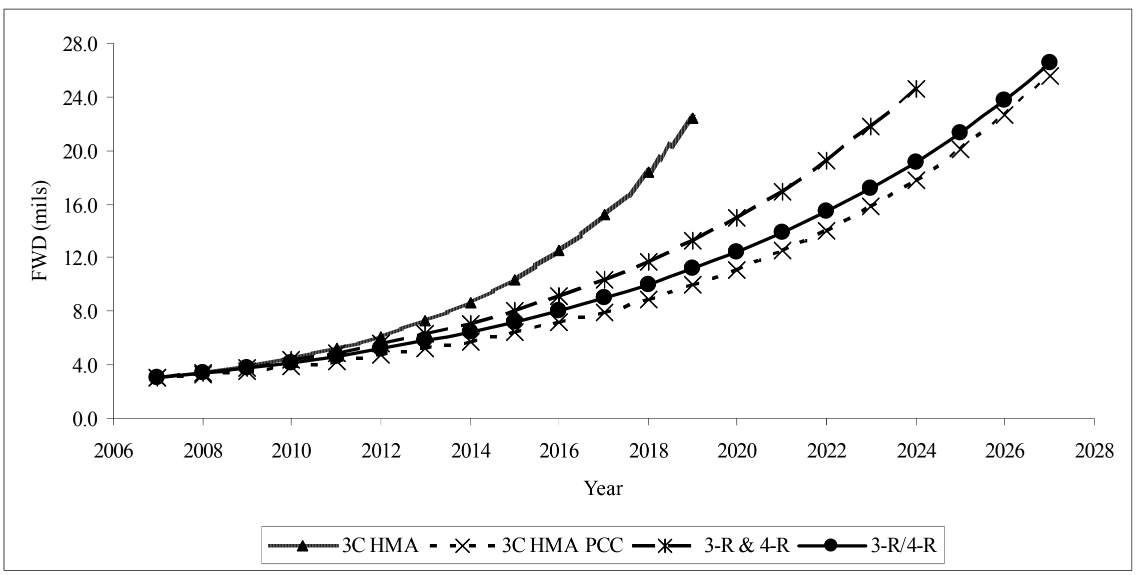

Figure 4.49 FWD forecasts by treatment type for urban interstates

4.5.5. Urban Non-Interstate of the NHS Models: Forecasting the Pavement Condition

Using Equations (32) through (37) and the aforementioned assumptions (general assumptions, and assumptions specific to the urban non-interstate of the NHS models), the predicted values of the IRI (in/mi), PCR, rut depth (in), and surface deflection or FWD (mils) for the urban non-interstate of the NHS models of all the rehabilitation treatments are estimated, and the results are shown in Table 4.44. The prediction horizon is 20 years, and year t-1 is 2007 (the last year with available data); the first forecast year is 2008. As before, note that the missing values refer to predicted values of IRI greater than 350 in/mi, PCR less than zero (PCR cannot take negative values, or values greater than 100), rut depth greater than 1.5 inches, and surface deflection greater than 27 mils; the pavement condition corresponding to these values is typically too poor for one to come across in practice, hence their respected values are not illustrated.

Figures 4.50 through 4.53 present a graphical representation of these forecasts in time by rehabilitation treatment type, for the IRI, PCR, rut depth (RUT), and surface deflection (FWD), respectively.

Note that, over a twelve-year period (2007-2018), 2C HMA has a forecasted average deterioration in IRI, PCR, and RUT of 68 in/mi, 53, and 0.67 inches, respectively; and C PVM R of 113 in/mi, 26, and 0.6 inches, respectively. 3C HMA has a forecasted average deterioration in IRI, PCR, RUT, and FWD of 48 in/mi, 45, 0.09 inches, and 6.7 mils, respectively; 3C HMA PCC of 46 in/mi, 42, 0.08 inches, and 3.6 mils, respectively; 3-R & 4-R of 50 in/mi, 38, 0.41 inches, and 5.5 mils, respectively; and 3-R/4-R of 94 in/mi, 33, 0.15 inches, and 3.7 mils, respectively.

Table 4.44 Actual forecast values of the pavement condition for the urban non-interstates of the NHS models

2C HMA			
Year	IRI	PCR	RUT
2007	40	97	0.05
2008	43	94	0.08
2009	47	90	0.12
2010	52	86	0.17
2011	57	82	0.21
2012	62	77	0.27
2013	68	73	0.32
2014	75	67	0.39
2015	82	62	0.46
2016	90	56	0.54
2017	99	50	0.63
2018	108	44	0.72
2019	118	37	0.83
2020	128	29	0.95
2021	140	21	1.08
2022	152	13	1.23
2023	165	3	1.39
2024	178		
2025	193		
2026	209		
2027	225		

C PVM R			
Year	IRI	PCR	RUT
2007	40	97	0.05
2008	48	96	0.07
2009	56	94	0.09
2010	64	92	0.12
2011	73	90	0.15
2012	83	88	0.19
2013	93	86	0.24
2014	104	84	0.29
2015	115	81	0.36
2016	127	78	0.44
2017	140	75	0.53
2018	153	71	0.65
2019	167	68	0.78
2020	182	64	0.95
2021	198	60	1.14
2022	214	55	1.38
2023	232	50	
2024	250	45	
2025	270	40	
2026	290	35	
2027	312	29	

3C HMA				
Year	IRI	PCR	RUT	FWD
2007	40	97	0.05	3.0
2008	41	93	0.05	3.5
2009	42	90	0.05	4.1
2010	44	86	0.05	4.6
2011	47	82	0.05	5.2
2012	51	78	0.06	5.8
2013	55	74	0.07	6.4
2014	60	70	0.08	7.0
2015	66	65	0.09	7.7
2016	73	61	0.11	8.3
2017	80	56	0.12	9.0
2018	88	52	0.14	9.7
2019	98	47	0.17	10.4
2020	108	42	0.19	11.2
2021	119	37	0.22	11.9
2022	131	32	0.25	12.7
2023	144	26	0.29	13.5
2024	158	21	0.32	14.3
2025	173	15	0.36	15.2
2026	189	9	0.41	16.1
2027	207	4	0.45	17.0

3C HMA PCC				
Year	IRI	PCR	RUT	FWD
2007	40	97	0.05	3.0
2008	42	94	0.05	3.1
2009	45	90	0.05	3.2
2010	48	87	0.05	3.4
2011	52	83	0.05	3.7
2012	55	79	0.06	3.9
2013	59	75	0.06	4.2
2014	64	72	0.07	4.6
2015	69	68	0.08	5.0
2016	74	63	0.10	5.5
2017	79	59	0.11	6.0
2018	86	55	0.13	6.6
2019	92	51	0.14	7.2
2020	99	46	0.17	7.9
2021	106	41	0.19	8.6
2022	114	37	0.21	9.4
2023	123	32	0.24	10.2
2024	132	27	0.27	11.2
2025	141	22	0.31	12.1
2026	151	17	0.34	13.2
2027	162	11	0.38	14.3

3-R & 4-R				
Year	IRI	PCR	RUT	FWD
2007	40	97	0.05	3.0
2008	45	93	0.07	3.5
2009	49	90	0.10	3.9
2010	54	86	0.12	4.4
2011	58	82	0.15	4.9
2012	63	79	0.19	5.4
2013	67	75	0.22	5.9
2014	72	72	0.26	6.4
2015	76	69	0.31	6.9
2016	81	66	0.35	7.4
2017	86	62	0.41	8.0
2018	90	59	0.46	8.5
2019	95	56	0.53	9.1
2020	99	53	0.60	9.7
2021	104	50	0.67	10.3
2022	108	47	0.75	10.9
2023	113	44	0.85	11.5
2024	118	42	0.95	12.1
2025	122	39	1.06	12.7
2026	127	36	1.18	13.4
2027	131	34	1.31	14.0

3-R/4-R				
Year	IRI	PCR	RUT	FWD
2007	40	97	0.05	3.0
2008	48	92	0.05	3.2
2009	57	87	0.06	3.4
2010	66	83	0.07	3.6
2011	74	79	0.08	3.9
2012	83	76	0.09	4.2
2013	91	74	0.10	4.5
2014	100	71	0.11	4.8
2015	108	69	0.13	5.2
2016	117	67	0.15	5.7
2017	125	65	0.17	6.2
2018	134	64	0.20	6.7
2019	142	63	0.22	7.3
2020	151	62	0.25	8.0
2021	160	61	0.28	8.8
2022	168	60	0.32	9.7
2023	177	59	0.36	10.7
2024	186	58	0.40	11.7
2025	194	58	0.44	13.0
2026	203	57	0.48	14.3
2027	211	57	0.53	15.8

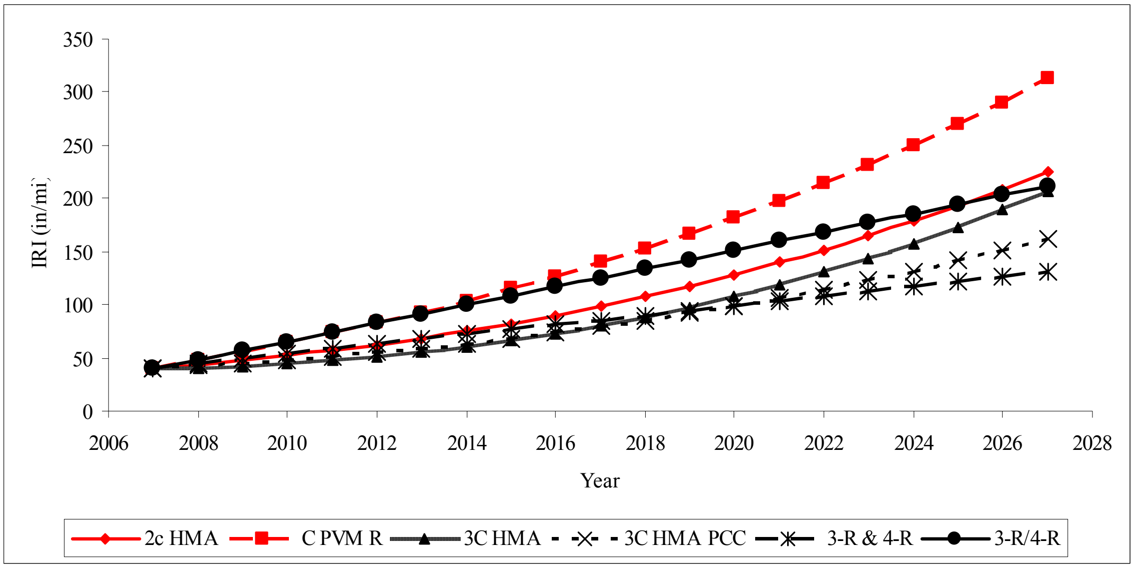

Figure 4.50 IRI forecasts by treatment type for urban non-interstates of the NHS

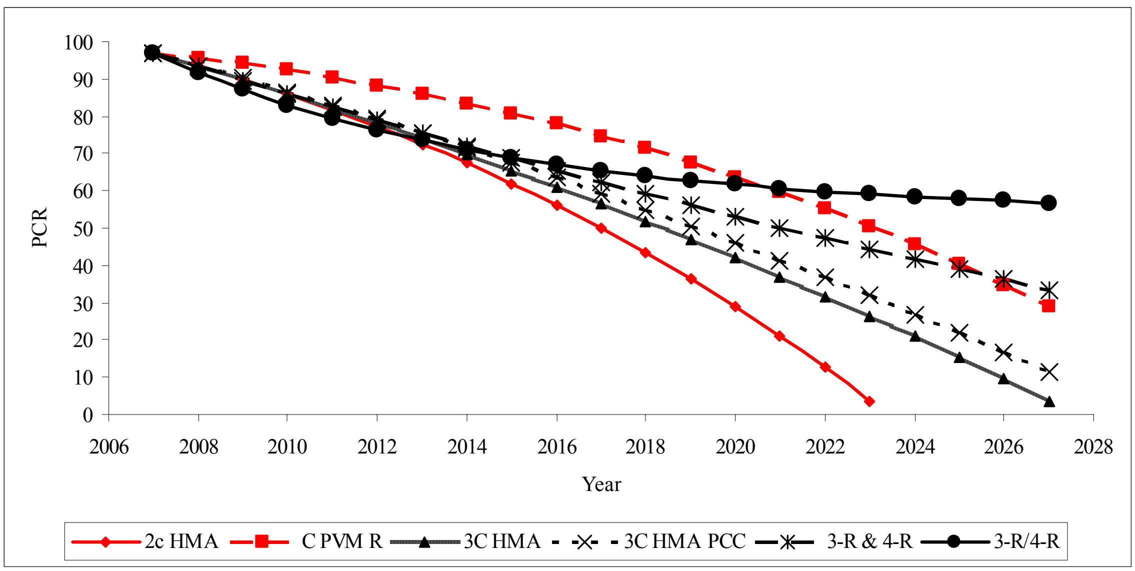

Figure 4.51 PCR forecasts by treatment type for urban non-interstates of the NHS

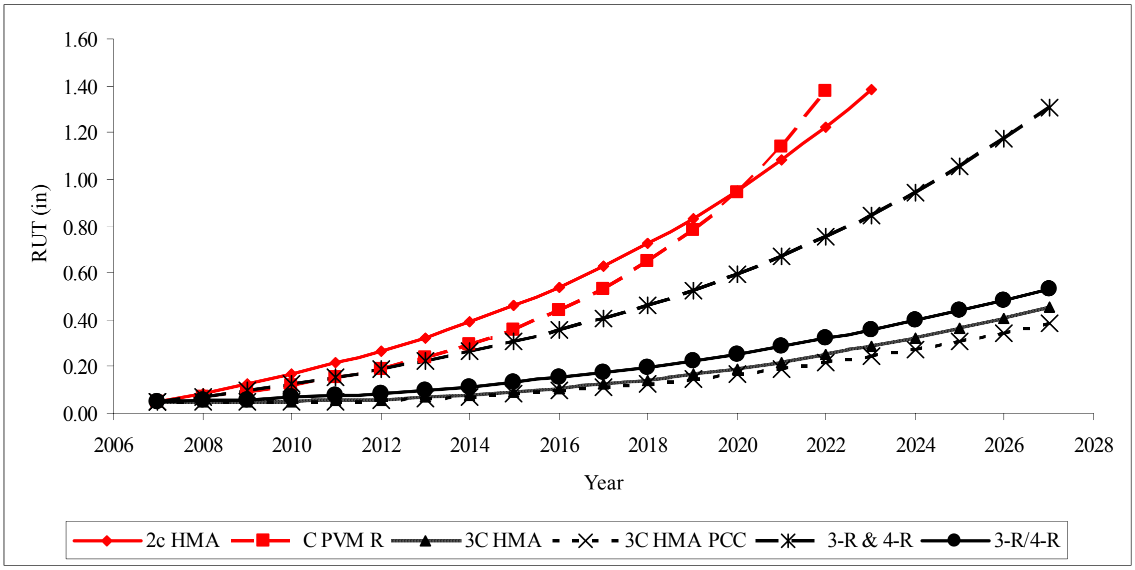

Figure 4.52 RUT forecasts by treatment type for urban non-interstates of the NHS

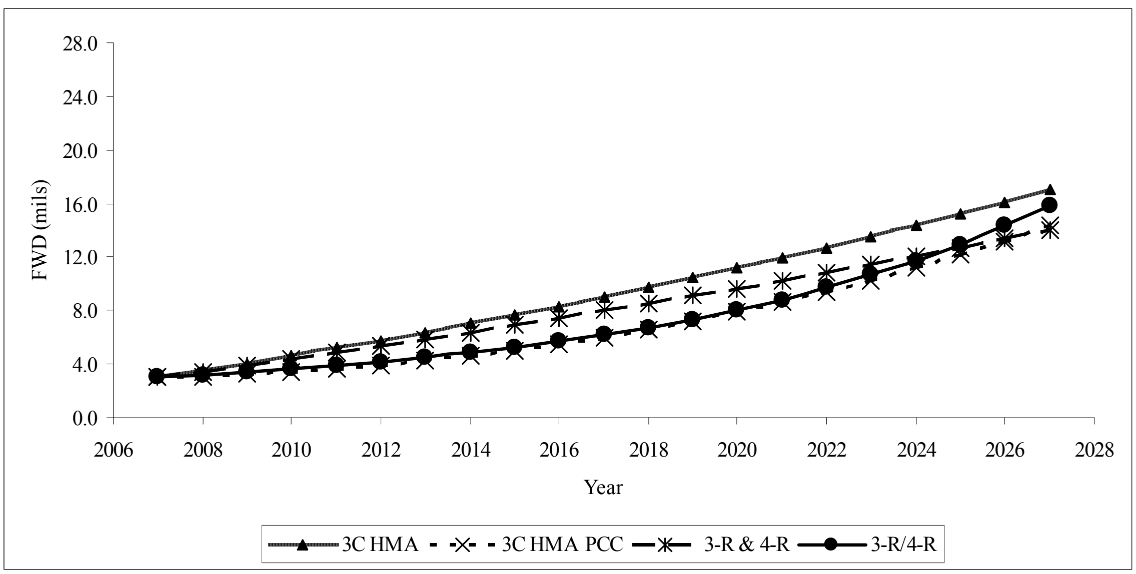

Figure 4.53 FWD forecasts by treatment type for urban non-interstates of the NHS

4.5.6. Urban Non-Interstate Non-NHS Models: Forecasting the Pavement Condition

Using Equations (38) through (43) and the aforementioned assumptions (general assumptions, and assumptions specific to the urban non-interstate non-NHS models), the predicted values of the IRI (in/mi), PCR, rut depth (in), and surface deflection or FWD (mils) for the urban non-interstate non-NHS models of all the rehabilitation treatments are estimated, and the results are shown in Table 4.45. The prediction horizon is 20 years, and year t-1 is 2007 (the last year with available data); the first forecast year is 2008. As before, note that the missing values refer to predicted values of IRI greater than 350 in/mi, PCR less than zero (PCR cannot take negative values, or values greater than 100), rut depth greater than 1.5 inches, and surface deflection greater than 27 mils; the pavement condition corresponding to these values is typically too poor for one to come across in practice, hence their respected values are not illustrated.

Figures 4.54 through 4.57 present a graphical representation of these forecasts in time by rehabilitation treatment type, for the IRI, PCR, rut depth (RUT), and surface deflection (FWD), respectively.

Note that, over a twelve-year period (2007-2018), 2C HMA has a forecasted average deterioration in IRI, PCR, and RUT of 49 in/mi, 62, and 0.67 inches, respectively; and C PVM R of 65 in/mi, 55, and 0.54 inches, respectively. 3C HMA has a forecasted average deterioration in IRI, PCR, RUT, and FWD of 106 in/mi, 26, 0.12 inches, and 14.2 mils, respectively; 3C HMA PCC of 29 in/mi, 43, 0.48 inches, and 14.5 mils, respectively; 3-R & 4-R of 25 in/mi, 11, 0.5 inches, and 2.1 mils, respectively; and 3-R/4-R of 35 in/mi, 43, 0.06 inches, and 9.3 mils, respectively.

Table 4.45 Actual forecast values of the pavement condition for the urban non-interstates non-NHS models

2C HMA				C PVM R				3C HMA					3C HMA PCC					3-R & 4-R					3-R/4-R				
Year	IRI	PCR	RUT	Year	IRI	PCR	RUT	Year	IRI	PCR	RUT	FWD	Year	IRI	PCR	RUT	FWD	Year	IRI	PCR	RUT	FWD	Year	IRI	PCR	RUT	FWD
2007	40	97	0.05	2007	40	97	0.05	2007	40	97	0.05	3.0	2007	40	97	0.05	3.0	2007	40	97	0.05	3.0	2007	40	97	0.05	3.0
2008	43	93	0.10	2008	45	93	0.10	2008	48	94	0.05	3.2	2008	42	94	0.08	3.8	2008	42	96	0.08	3.1	2008	43	92	0.05	3.4
2009	46	88	0.15	2009	50	88	0.14	2009	56	92	0.06	3.9	2009	42	90	0.12	4.4	2009	42	95	0.11	3.3	2009	46	88	0.06	3.8
2010	49	83	0.20	2010	55	83	0.19	2010	65	89	0.07	4.6	2010	44	87	0.16	5.1	2010	43	95	0.15	3.4	2010	48	83	0.06	4.3
2011	53	78	0.26	2011	61	79	0.24	2011	74	87	0.07	5.4	2011	45	83	0.19	6.0	2011	45	94	0.19	3.6	2011	51	79	0.06	4.9
2012	57	73	0.31	2012	66	74	0.29	2012	83	85	0.08	6.4	2012	47	80	0.24	6.9	2012	46	93	0.23	3.8	2012	53	75	0.07	5.6
2013	61	67	0.37	2013	72	69	0.34	2013	93	82	0.09	7.6	2013	49	76	0.28	8.1	2013	48	92	0.27	4.0	2013	57	71	0.07	6.4
2014	66	61	0.44	2014	78	64	0.38	2014	103	80	0.10	8.9	2014	52	72	0.32	9.4	2014	50	91	0.32	4.2	2014	60	67	0.08	7.2
2015	71	55	0.50	2015	85	59	0.43	2015	113	77	0.12	10.5	2015	55	68	0.37	11.0	2015	52	90	0.37	4.4	2015	63	63	0.09	8.2
2016	76	49	0.57	2016	91	53	0.48	2016	124	75	0.13	12.4	2016	59	63	0.42	12.8	2016	56	89	0.43	4.6	2016	67	60	0.09	9.4
2017	82	42	0.64	2017	98	48	0.53	2017	135	73	0.15	14.6	2017	64	59	0.47	15.0	2017	59	87	0.49	4.8	2017	70	57	0.10	10.7
2018	89	35	0.72	2018	105	42	0.59	2018	146	71	0.17	17.2	2018	69	54	0.53	17.5	2018	65	86	0.55	5.1	2018	75	54	0.11	12.3
2019	96	28	0.80	2019	113	36	0.64	2019	158	68	0.19	20.3	2019	76	49	0.58	20.5	2019	71	85	0.62	5.4	2019	79	51	0.12	14.0
2020	104	20	0.88	2020	121	30	0.69	2020	170	66	0.21	23.8	2020	85	44	0.64	24.0	2020	79	84	0.70	5.7	2020	85	48	0.13	16.1
2021	112	12	0.97	2021	129	24	0.74	2021	183	64	0.23		2021	93	38	0.71		2021	87	82	0.78	6.0	2021	91	45	0.14	18.4
2022	121	4	1.06	2022	137	18	0.79	2022	197	61	0.26		2022	103	33	0.77		2022	96	81	0.87	6.3	2022	97	42	0.15	21.1
2023	131		1.16	2023	145	12	0.85	2023	210	59	0.29		2023	115	27	0.84		2023	108	79	0.97	6.6	2023	106	40	0.17	24.2
2024	141		1.26	2024	154	5	0.90	2024	225	57	0.32		2024	129	21	0.91		2024	121	78	1.07	7.0	2024	115	37	0.18	
2025	153		1.37	2025	164		0.96	2025	239	55	0.36		2025	137	14	0.99		2025	132	76	1.18	7.4	2025	126	35	0.19	
2026	165		1.48	2026	173		1.01	2026	255	53	0.40		2026	154	8	1.07		2026	143	74	1.30	7.8	2026	141	32	0.21	
2027	178			2027	183		1.07	2027	271	50	0.44		2027	173	1	1.15		2027	157	72	1.43	8.3	2027	151	30	0.22	

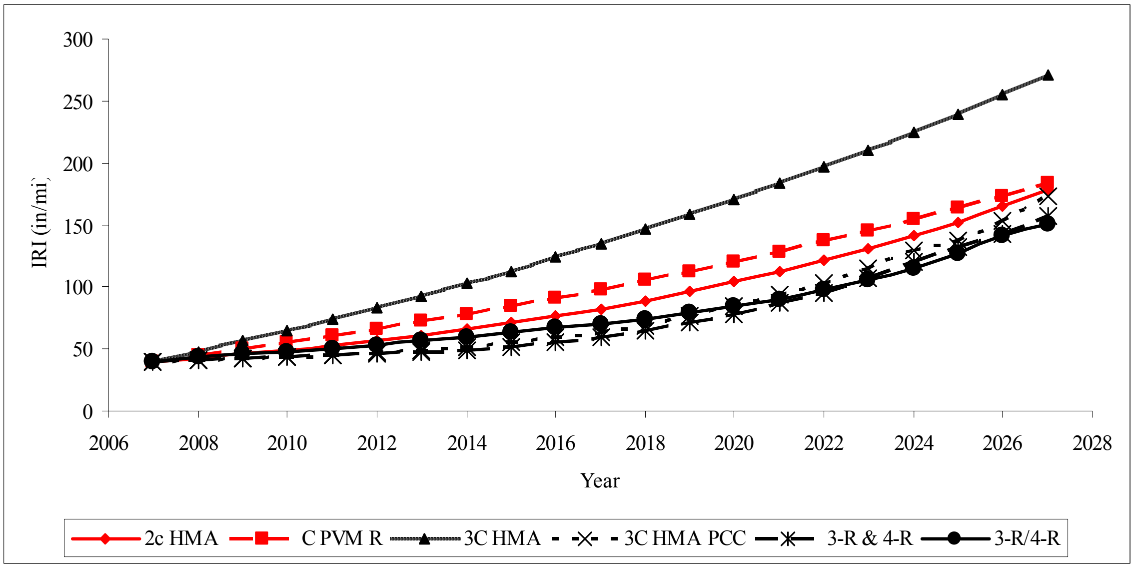

Figure 4.54 IRI forecasts by treatment type for urban non-interstates non-NHS

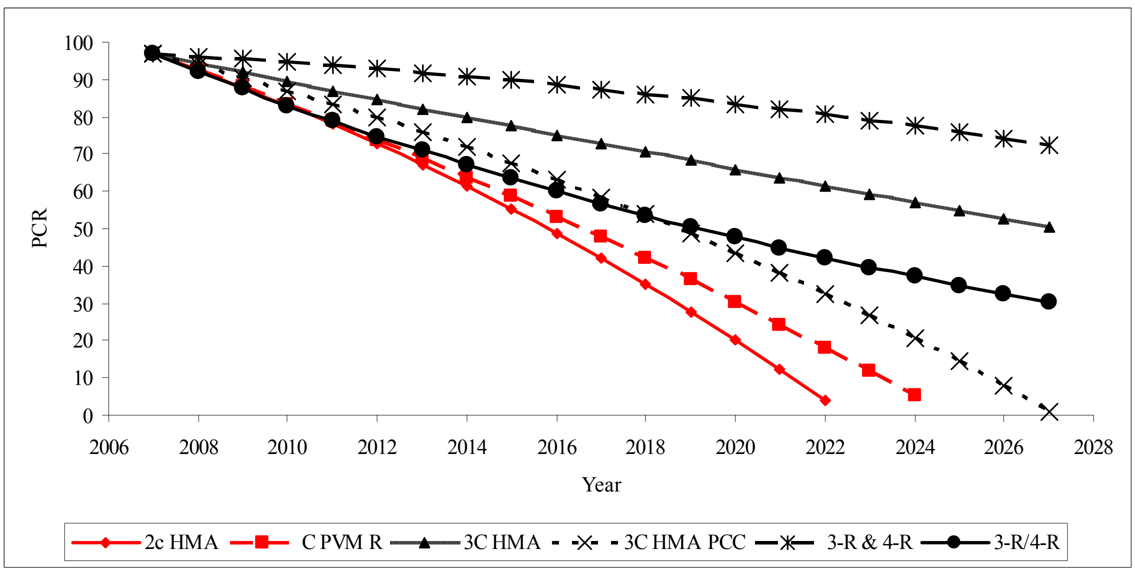

Figure 4.55 PCR forecasts by treatment type for urban non-interstates non-NHS

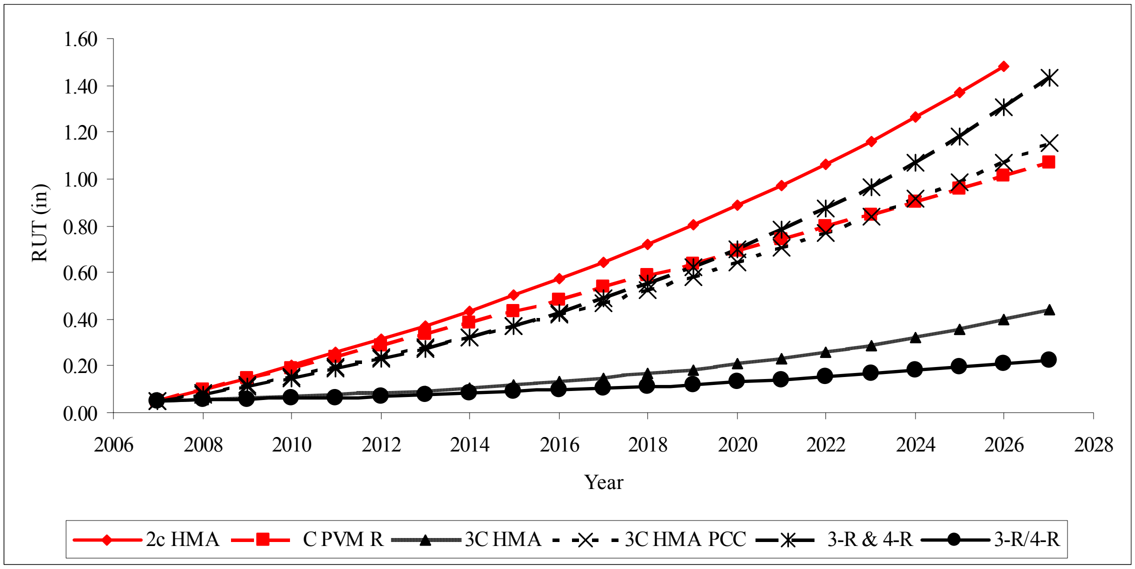

Figure 4.56 RUT forecasts by treatment type for urban non-interstates non-NHS

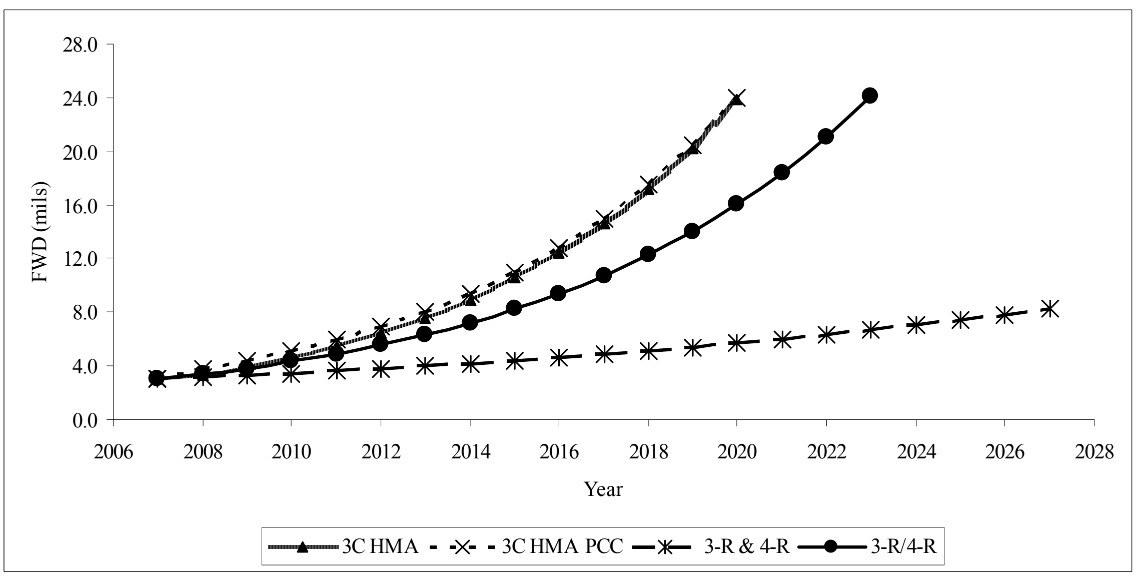

Figure 4.57 FWD forecasts by treatment type for urban non-interstates non-NHS

4.5.7. Forecasting Accuracy of the Models

To further evaluate the forecasting accuracy of the developed models, the mean absolute percent error (MAPE) can be estimated as follows (Washington et al., 2003):

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|PE_i\right| \tag{45}$$

where $PE_i = 100 \cdot (X_i - F_i)/X_i$ is the percentage error for observation *i* of the actual, X, and predicted, F, value of the pavement condition indicator.

Table 4.46 presents the forecasting accuracy results through application of the MAPE measure (this measure eliminates the effect of observed data variability). The MAPE values closer to zero, signify better accuracy. A MAPE of 0.0486 (as in the IRI equation of the two-course HMA overlay with or without surface milling for the rural interstate model) indicates that on average, the forecasts under or overestimate the true values by 4.86%. Note that the range of the MAPE for all the models is from 0.00042 (as in the rut depth equation of the three-course HMA with crack and seat of PCC pavement for the rural non-interstates of the NHS model) which indicates that the forecasts under or overestimate the true values by only 0.042% (almost perfect prediction), to 0.1345 (as in the PCR equation of the three-course HMA overlay with or without surface milling for the rural non-interstates non-NHS model) which indicates that the forecasts are under or overestimated (with respect to the true values) by 13.45% (still a very good approximation).

Table 4.46 MAPE values for all rehabilitation treatments by road functional class

		Pavement Rehabilitation Treatment Types					
		Functional Treatments		Structural Treatments			
		2C HMA	C PVM R	3C HMA	3C HMA PCC	3-R & 4-R	3-R/4-R
Rural Interstates	IRI	0.0486	0.0037	0.0347	0.0518	0.0495	0.0335
	PCR	0.0175	0.0702	0.0939	0.0766	0.0444	0.0008
	RUT	0.0442	0.0034	0.0272	0.0547	0.0120	0.0241
	FWD	0.0137	0.0451	0.0426	0.0272	0.0098	0.0133
Rural Non-Interstates of the NHS	IRI	0.0485	0.0105	0.0487	0.0512	0.0104	0.0532
	PCR	0.0427	0.0572	0.0753	0.0565	0.0070	0.0260
	RUT	0.0076	0.0119	0.0493	0.0004	0.0381	0.0617
	FWD	0.0199	0.0268	0.0088	0.0032	0.0014	0.0308
Rural Non-Interstates Non-NHS	IRI	0.0233	0.0506	0.0588	0.0262	0.0311	0.0536
	PCR	0.0298	0.0504	0.1345	0.0535	0.0644	0.0469
	RUT	0.0563	0.0256	0.0388	0.0576	0.0092	0.0194
	FWD	0.0336	0.0142	0.0142	0.0380	0.0218	0.0239
Urban Interstates	IRI	0.0454	0.0211	0.0535	0.0357	0.0780	0.0295
	PCR	0.0711	0.0175	0.1116	0.0473	0.0165	0.1119
	RUT	0.0644	0.0045	0.0219	0.0355	0.0152	0.0806
	FWD	0.0201	0.0256	0.0067	0.0013	0.0391	0.0316
Urban Non-Interstates of the NHS	IRI	0.0070	0.0519	0.0184	0.0461	0.0050	0.0167
	PCR	0.0842	0.0007	0.0755	0.0199	0.0046	0.0815
	RUT	0.0442	0.0052	0.0295	0.0412	0.0010	0.0143
	FWD	0.0011	0.0310	0.0181	0.0349	0.0280	0.0195
Urban Non-Interstates Non-NHS	IRI	0.0518	0.0165	0.0297	0.0621	0.0568	0.0019
	PCR	0.1076	0.0830	0.1162	0.1094	0.0927	0.0085
	RUT	0.0371	0.0322	0.0464	0.0357	0.0245	0.0093
	FWD	0.0440	0.0218	0.0348	0.0292	0.0346	0.0073

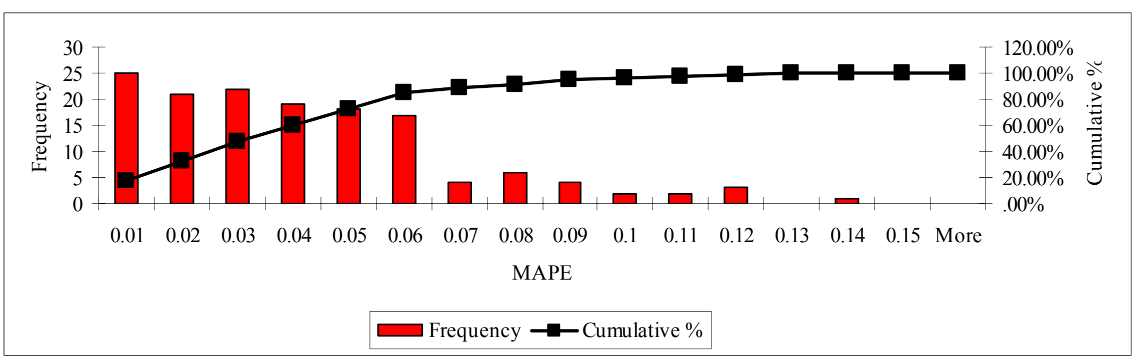

Figure 4.58 MAPE distribution

Figure 4.58 presents the distribution of the estimated MAPE values. It can be observed that the vast majority (more then 75%) of the pavement condition equations have a MAPE value of less than 0.05, indicating that the forecasts under or overestimate the true values by 5% or less; whereas, less than 5% of the pavement equations have a MAPE value greater than 0.10 (which indicates that the forecasts under or overestimate the true values by 10% or more). As such, the MAPE values in Table 4.46 illustrate that the model forecasts are considerably accurate.

4.6. Service Lives of Pavement Rehabilitation Treatments

The remaining pavement service life represents its remaining useable life until a pavement performance condition threshold is surpassed; it can be defined as the time from its current status to the time that some treatment is needed to make the pavement operational (to return the pavement's condition to a good operational status). However, a pavement may be treated long before or even long after its condition requires it. Hence, forecasting pavement condition and identification of physical condition thresholds that initiate the treatment, is very important. The combined use of pavement-performance forecasting and condition thresholds, allows for a reliable estimation of the pavement's service life from the implementation of a specific treatment.

The pavement service life Δ_i for a pavement i can be estimated as follows:

$$\Delta_i = \sum_{n}^{\kappa} \left(t_{in} \mid PI_n \le PI_\kappa \right), \; PI_\kappa = \min\{PI_n\} \tag{46}$$

where, t_{in} is one year of service life of pavement i for the time period n, given that the pavement performance indicator in year n, PI_n, is lower than or equal to the critical pavement performance indicator (i.e., the performance threshold) PI_κ. Note that PI_κ is the minimum acceptable level of performance indicator PI_n of the pavement. Also, for a new or preserved pavement, $n = 1$.

Anastasopoulos (2009) developed a methodology to estimate objectively defined safety-based thresholds of the performance condition indicators that initiate the pavement treatment. Table 4.47 presents the pavement condition lower-, mid-, and upper-thresholds (i.e., IRI, PCR, RUT, and FWD) by road functional class, respectively.

Table 4.47 Pavement condition thresholds by road functional class (Source: Anastasopoulos, 2009)

Functional Class:		Rural Roads			Urban Roads		
		Interstates	Non-Interstates of the NHS	Non-Interstates Non-NHS	Interstates	Non-Interstates of the NHS	Non-Interstates Non-NHS
Lower-Threshold Value	IRI	146.7	178.7	185.5	150.3	169.5	183.9
	PCR	56.0	67.4	57.7	65.6	65.6	56.1
	RUT	0.48	0.43	0.48	0.37	0.42	0.48
	FWD	11.3	14.5	18.9	16.5	14.2	20.1
Mid-Threshold Value	IRI	172.6	188.9	200.5	182.5	194.3	180.8
	PCR	53.2	64.9	52.2	52.0	56.8	49.4
	RUT	0.51	0.44	0.50	0.44	0.48	0.51
	FWD	13.3	15.2	20.9	21.9	16.4	22.6
Upper-Threshold Value	IRI	192.1	210.8	223.0	202.2	212.6	201.5
	PCR	43.5	59.8	44.0	43.7	50.2	41.3
	RUT	0.55	0.47	0.54	0.49	0.53	0.55
	FWD	14.9	16.6	23.8	25.3	18.1	25.6

4.6.1. Graphical Approximation of the pavement Service Life

The pavement service life can be graphically approximated by first modeling and forecasting pavement performance, and then by using pavement performance thresholds, as those in Table 4.47. The pavement performance can be projected in the future, and the pavement service life is terminated when the pavement performance surpasses the performance threshold.

Figure 4.59 illustrates an approximation of the pavement service life and remaining service life using a performance curve (forecast of the pavement performance over time) and a pavement performance threshold (a critical value of the pavement performance that some treatment needs to occur). As such, the pavement service life can be estimated to be t_κ - t_1 (and the corresponding pavement performance drop is PI_κ - PI_1), whereas the remaining service life of the pavement is t_κ - t_n (and the corresponding pavement performance drop is PI_κ - PI_n).

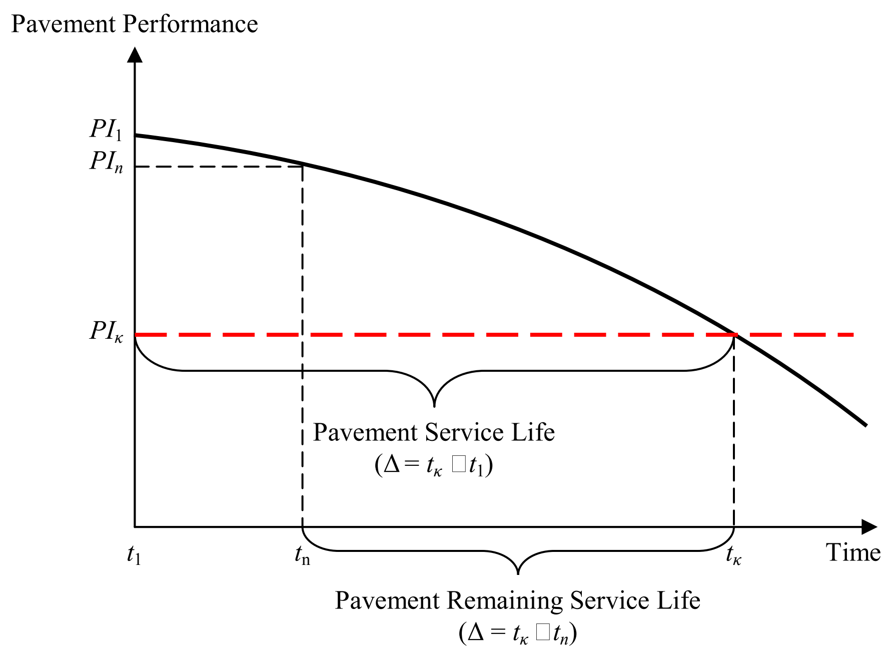

Figure 4.59 Graphical approximation of the pavement service life and remaining service life

For example, to approximate graphically the service life of the treatments[33] for rural and urban interstates, non-interstate roads of the National Highway System (NHS), and non-interstate non-NHS roads, the following *a priori* assumptions are made.

[33] 2c HMA: two-course HMA overlay with or without surface milling; C PVM R: concrete pavement restoration; 3C HMA: three-course HMA overlay with or without surface milling; 3C HMA PCC: three-course HMA overlay with crack and seat of PCC pavement; 3-R & 4-R: 3-R and 4-R overlay treatments; 3-R/4-R: 3-R/4-R pavement replacement treatments.

All road functional classes:

- Base Year = 2006
- Year of 1st Forecast, t = 2008
- Year before the Forecast Year, t-1 = 2007
- Base IRI = 30 in/mi
- Base PCR = 100
- Base RUT = 0.02 in
- Base FWD = 2 mils (for structural treatments only)
- IRI t-1 = 40 in/mi
- PCR t-1 = 97
- RUT t-1 = 0.05 in
- FWD t-1 = 3 mils (for structural treatments only)
- Drainage class = Well drained
- Prediction horizon = 20 years
- Yearly increase in AADT = 3%

Rural interstates:

- Contract Cost per mile = 350,000 USD
- AADT = 32,000 veh/day
- Percentage of Commercial Trucks = 25%

Rural non-interstates of the NHS:

- Contract Cost per mile = 288,000 USD
- AADT = 10,000 veh/day
- Percentage of Commercial Trucks = 15%

Rural non-interstates non-NHS:

- Contract Cost per mile = 160,000 USD
- AADT = 6,000 veh/day
- Percentage of Commercial Trucks = 11%

Urban interstates:

- Contract Cost per mile = 484,000 USD
- AADT = 26,000 veh/day
- Percentage of Commercial Trucks = 35%

Urban non-interstates of the NHS:

- Contract Cost per mile = 268,000 USD
- AADT = 9,000 veh/day
- Percentage of Commercial Trucks = 18%

Urban non-interstates non-NHS:

- Contract Cost per mile = 107,000 USD
- AADT = 4,000 veh/day
- Percentage of Commercial Trucks = 12%

Figures 4.60 through 4.83 present the pavement performance deterioration curves (i.e., IRI, PCR, rut depth, and surface deflection, respectively) of the six treatments and their corresponding lower-, mid-, and upper-thresholds, for rural and urban interstates, non-interstate roads of the National Highway System (NHS), and non-interstate non-NHS roads, respectively.

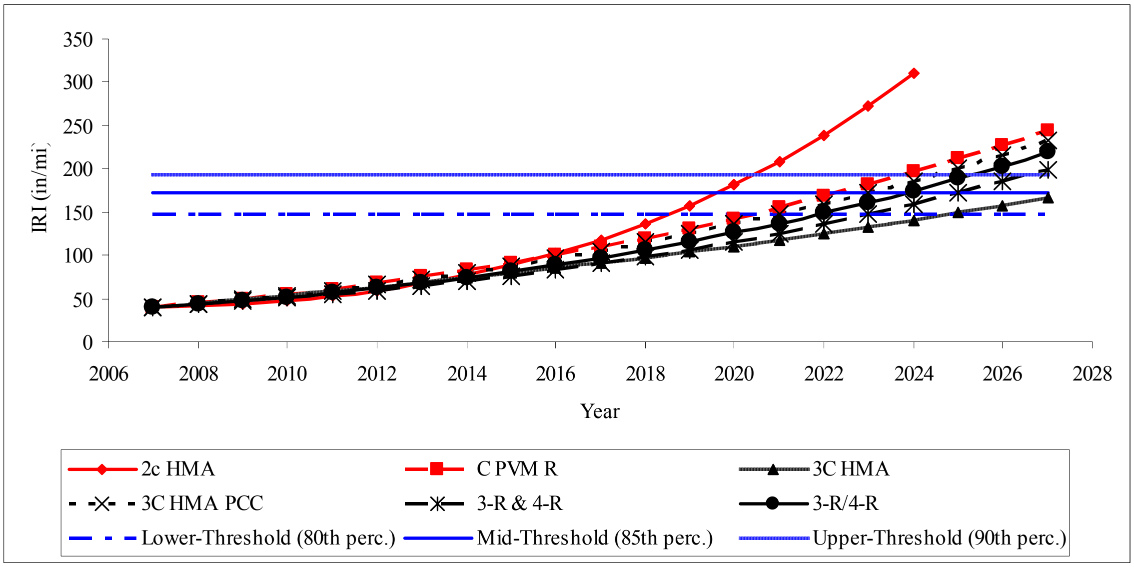

Figure 4.60 IRI forecasts and thresholds for rural interstates

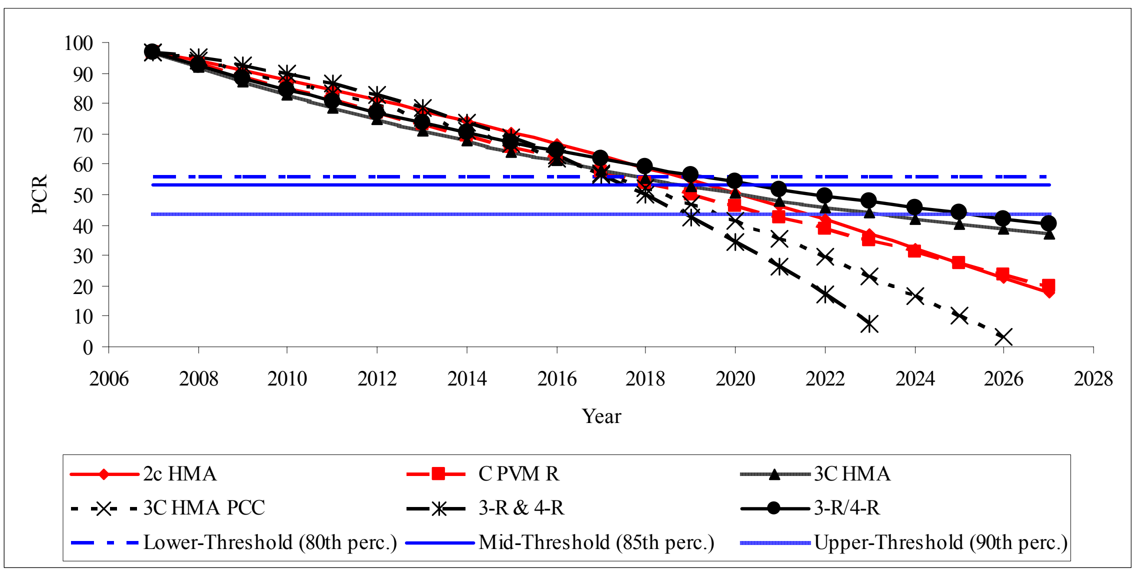

Figure 4.61 PCR forecasts and thresholds for rural interstates

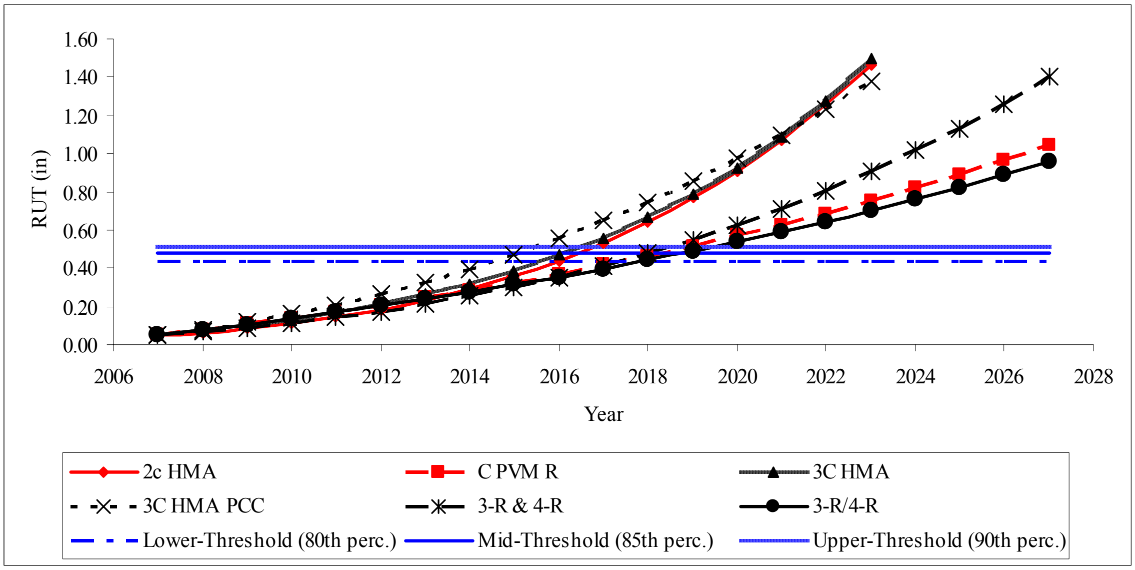

Figure 4.62 RUT forecasts and thresholds for rural interstates

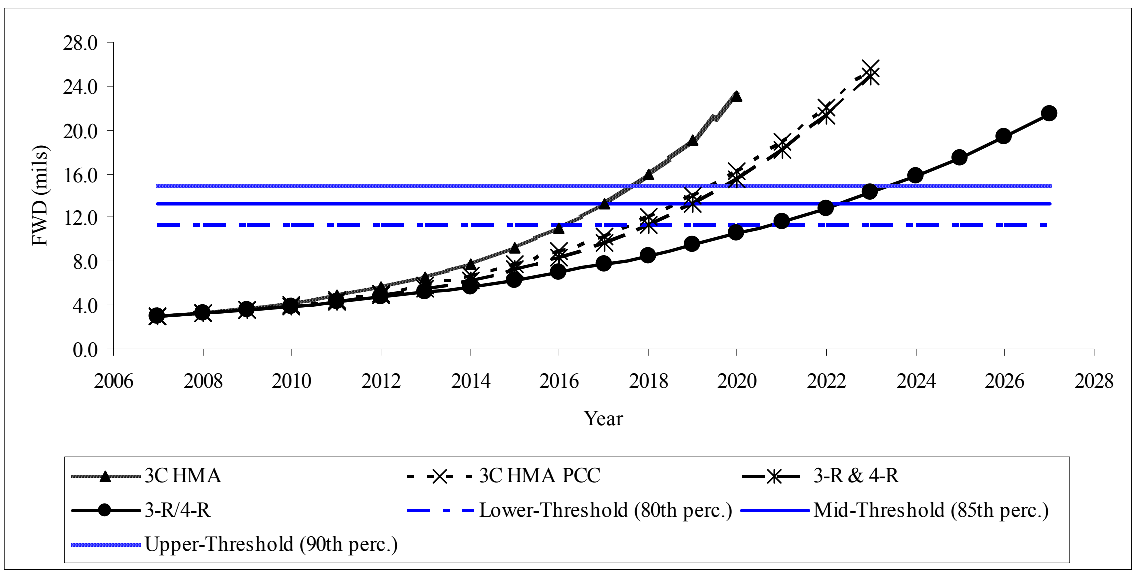

Figure 4.63 FWD forecasts and thresholds for rural interstates

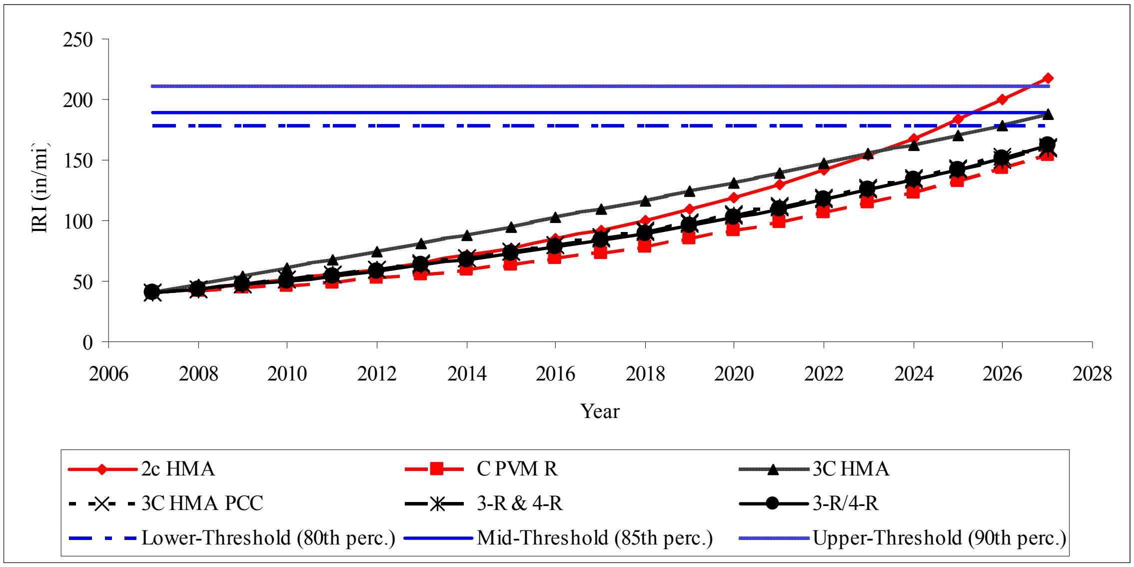

Figure 4.64 IRI forecasts and thresholds for rural non-interstates of the NHS

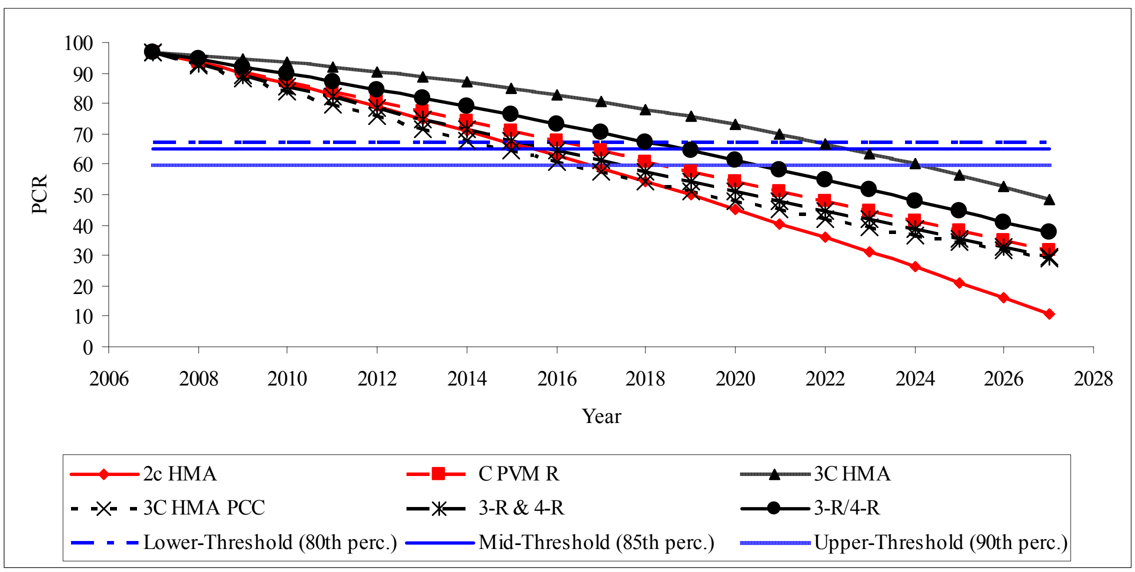

Figure 4.65 PCR forecasts and thresholds for rural non-interstates of the NHS

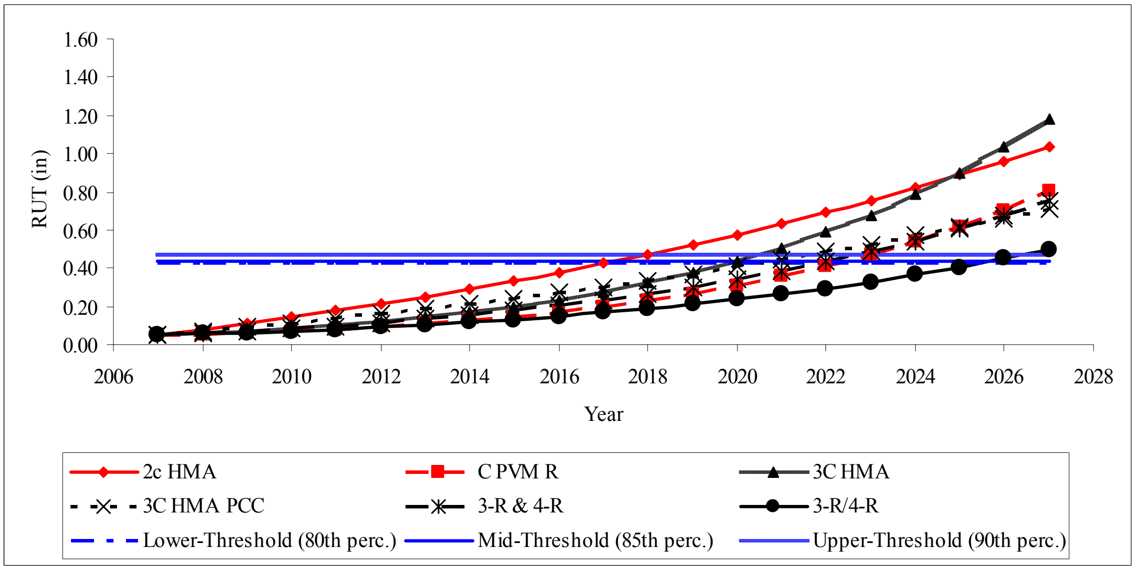

Figure 4.66 RUT forecasts and thresholds for rural non-interstates of the NHS

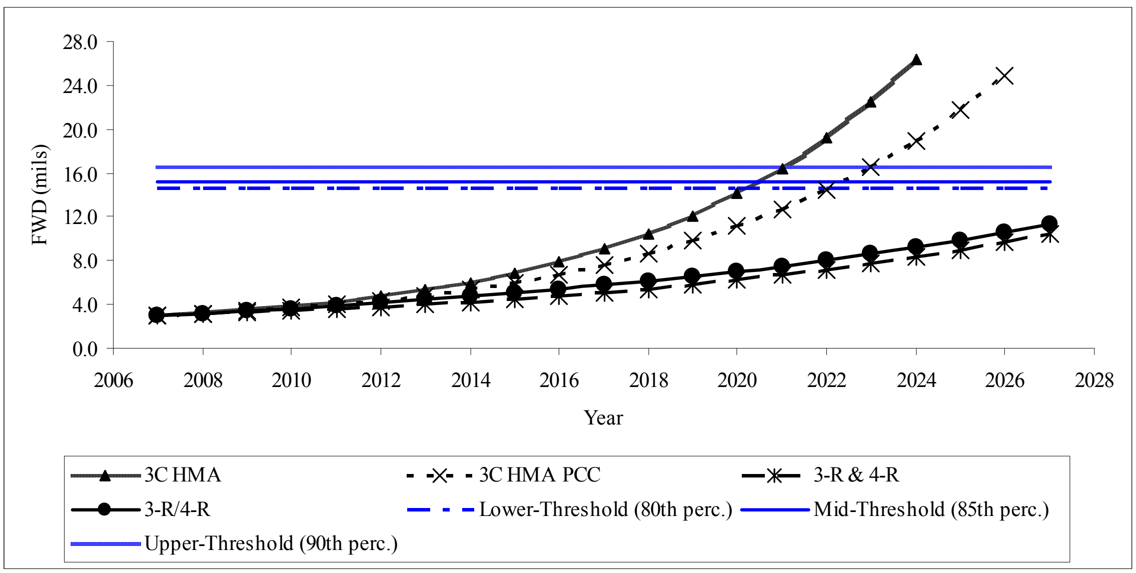

Figure 4.67 FWD forecasts and thresholds for rural non-interstates of the NHS

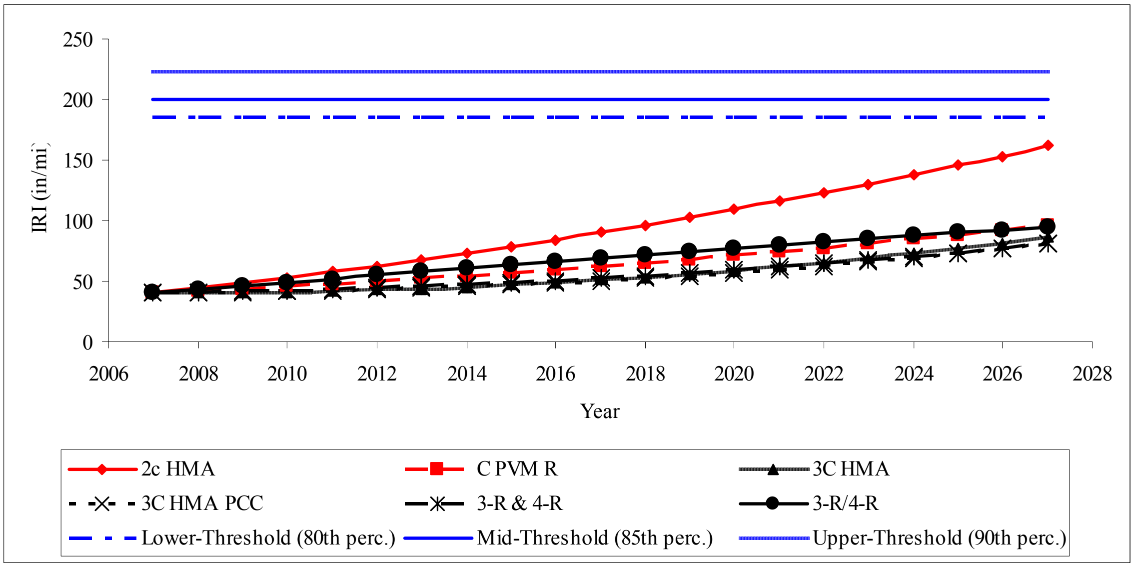

Figure 4.68 IRI forecasts and thresholds for rural non-interstates non-NHS

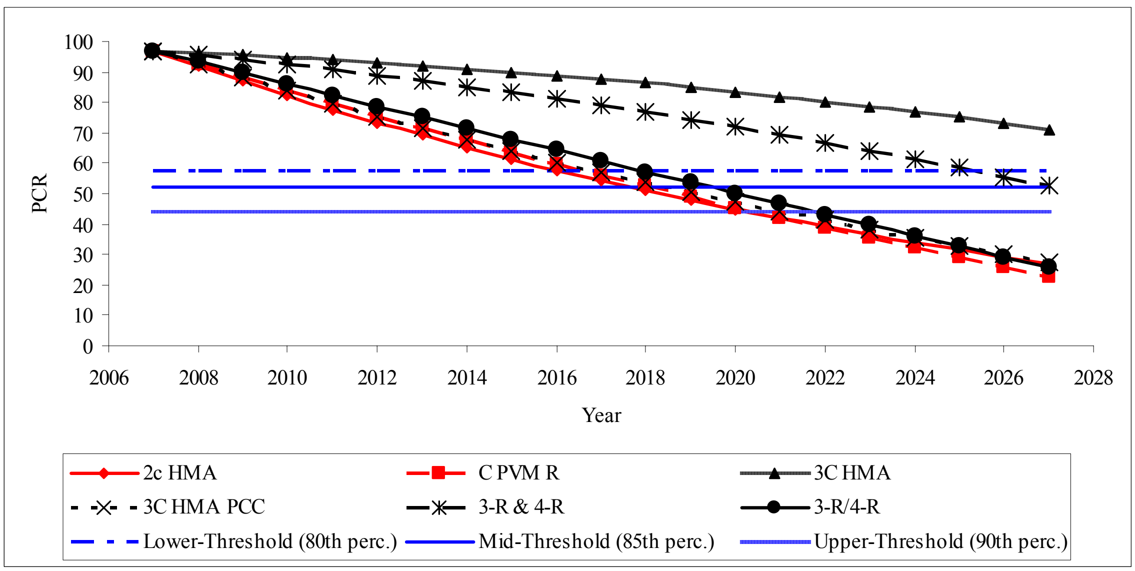

Figure 4.69 PCR forecasts and thresholds for rural non-interstates non-NHS

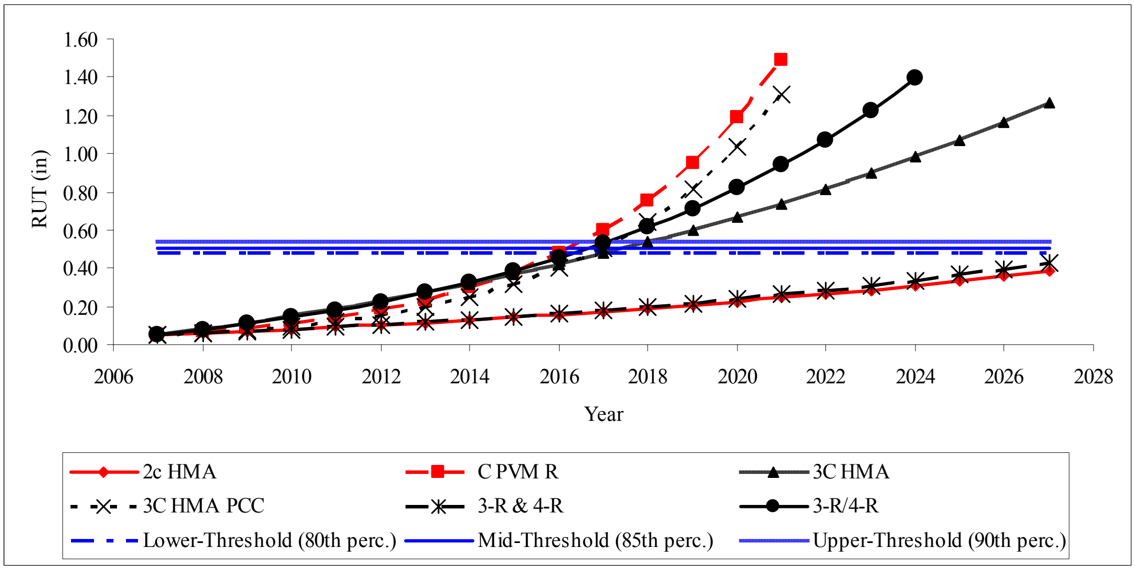

Figure 4.70 RUT forecasts and thresholds for rural non-interstates non-NHS

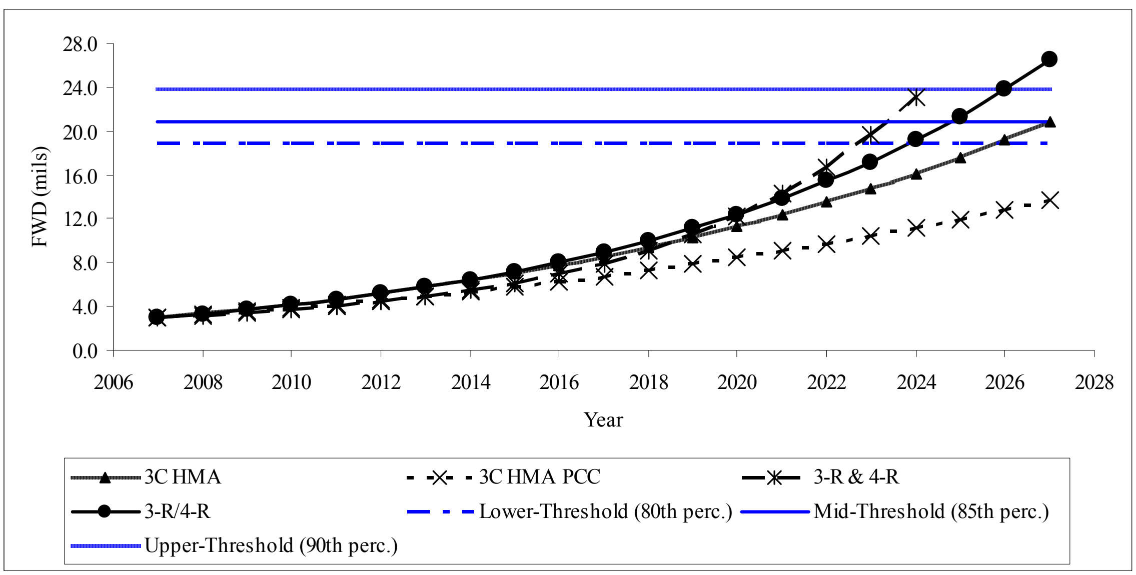

Figure 4.71 FWD forecasts and thresholds for rural non-interstates non-NHS

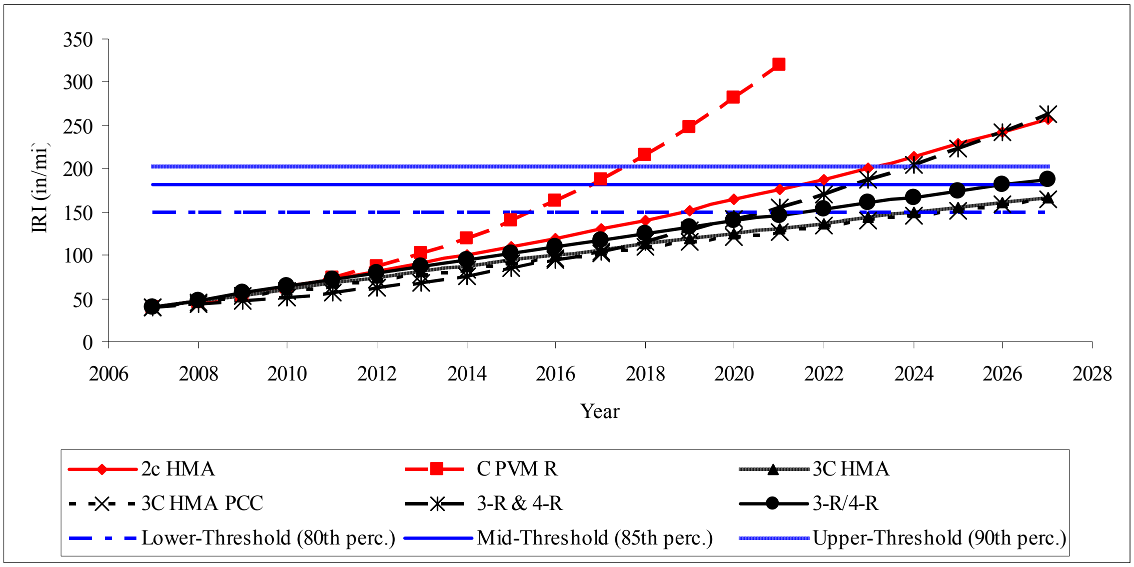

Figure 4.72 IRI forecasts and thresholds for urban interstates

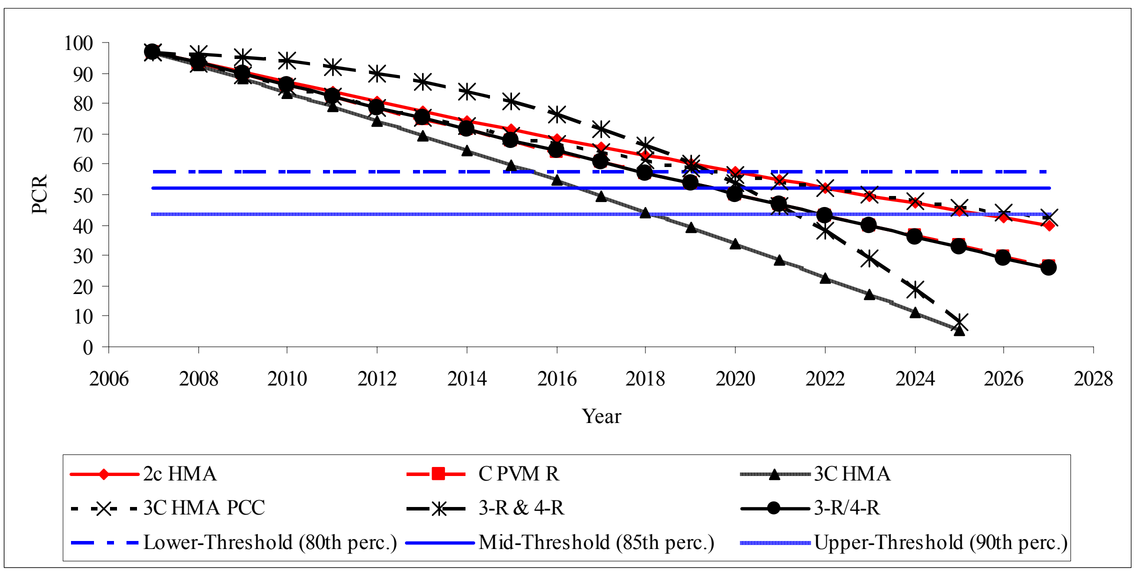

Figure 4.73 PCR forecasts and thresholds for urban interstates

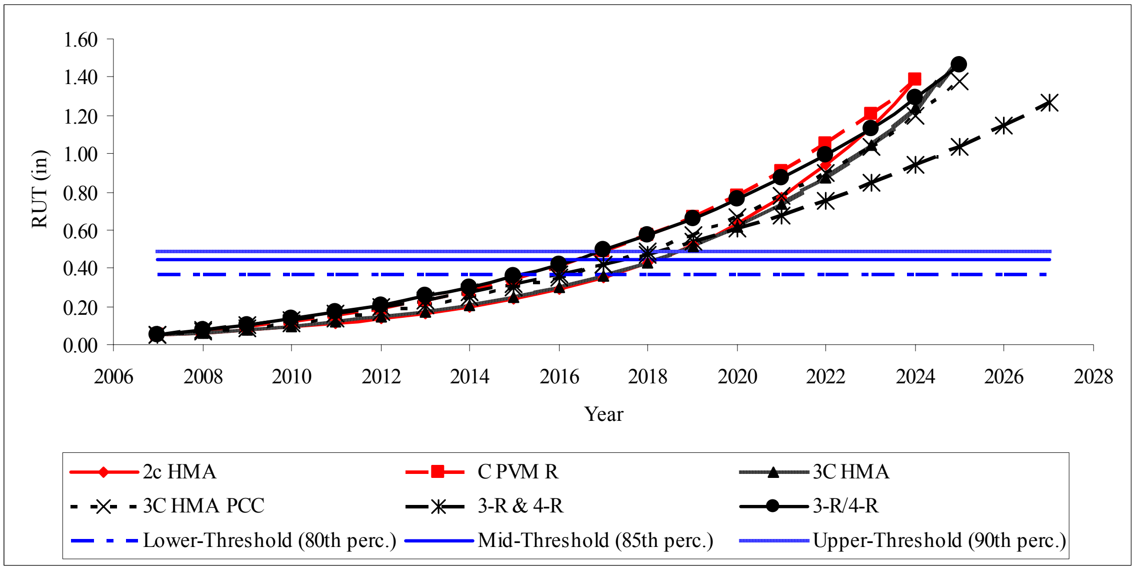

Figure 4.74 RUT forecasts and thresholds for urban interstates

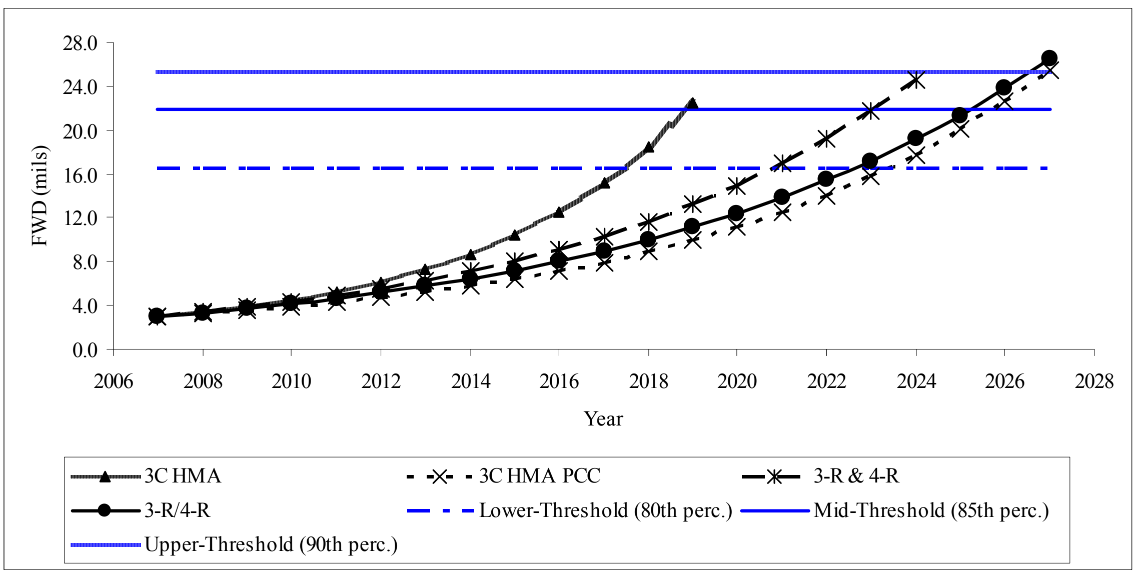

Figure 4.75 FWD forecasts and thresholds for urban interstates

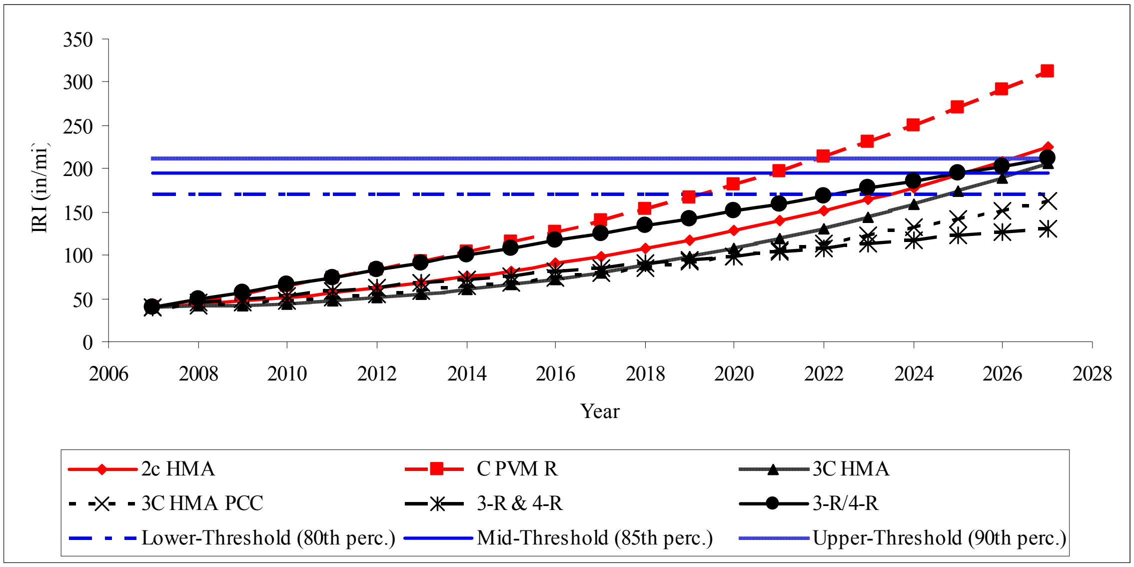

Figure 4.76 IRI forecasts and thresholds for urban non-interstates of the NHS

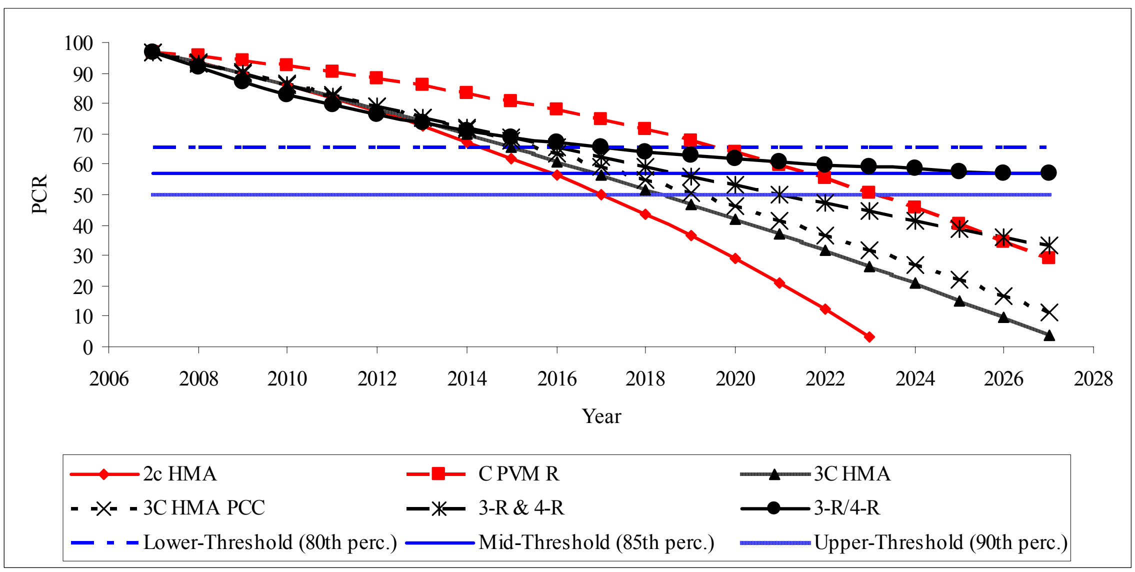

Figure 4.77 PCR forecasts and thresholds for urban non-interstates of the NHS

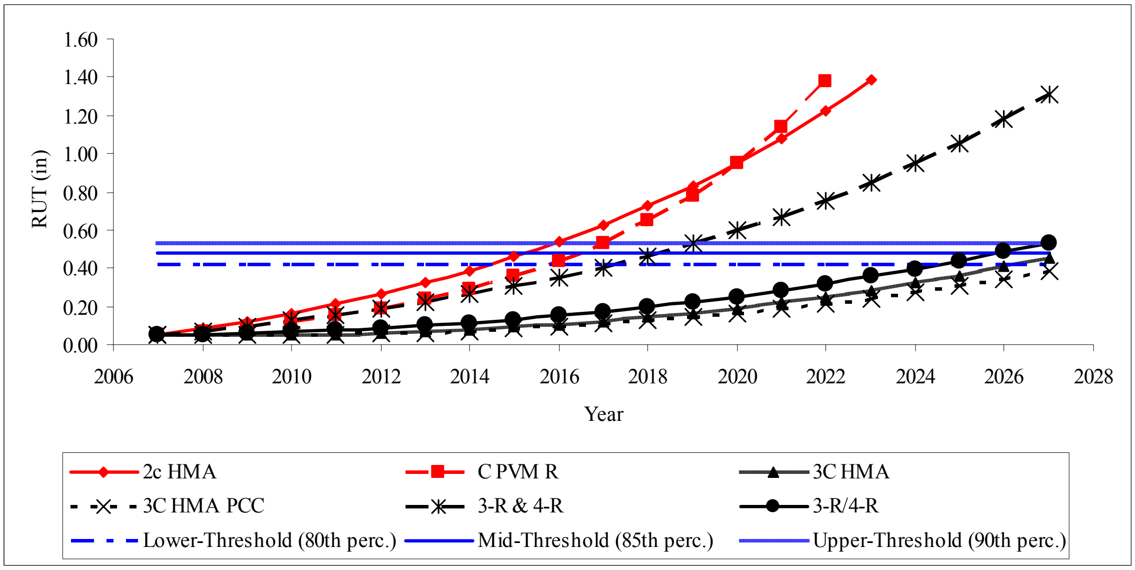

Figure 4.78 RUT forecasts and thresholds for urban non-interstates of the NHS

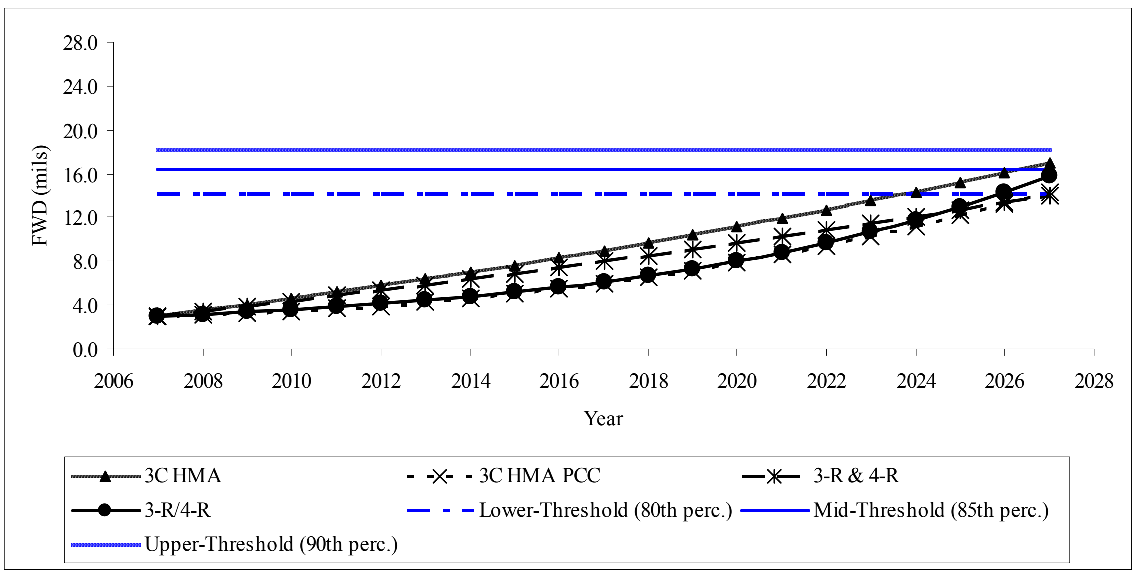

Figure 4.79 FWD forecasts and thresholds for urban non-interstates of the NHS

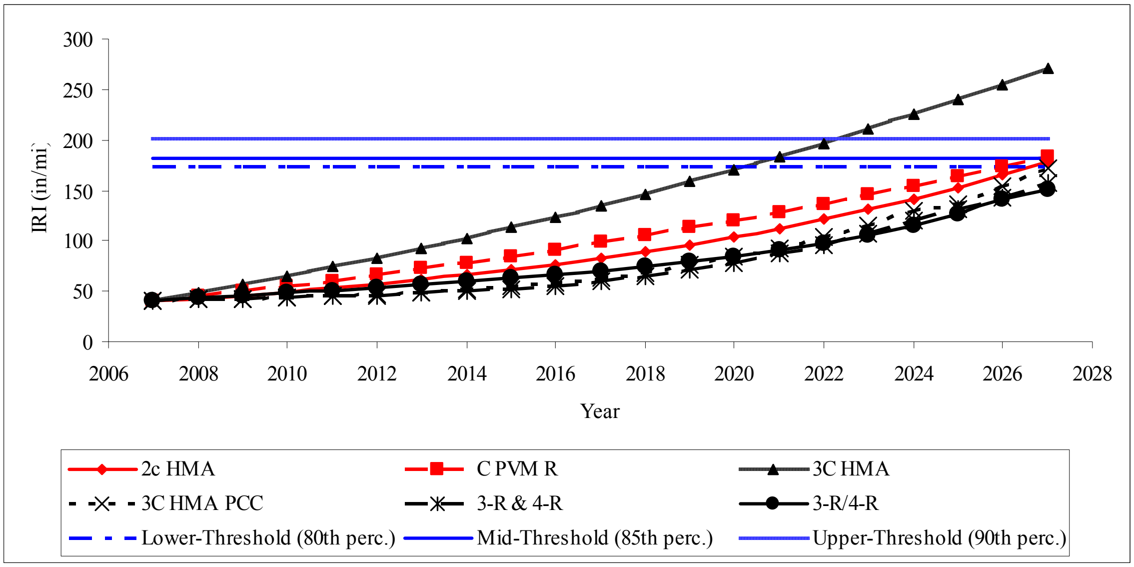

Figure 4.80 IRI forecasts and thresholds for urban non-interstates non-NHS

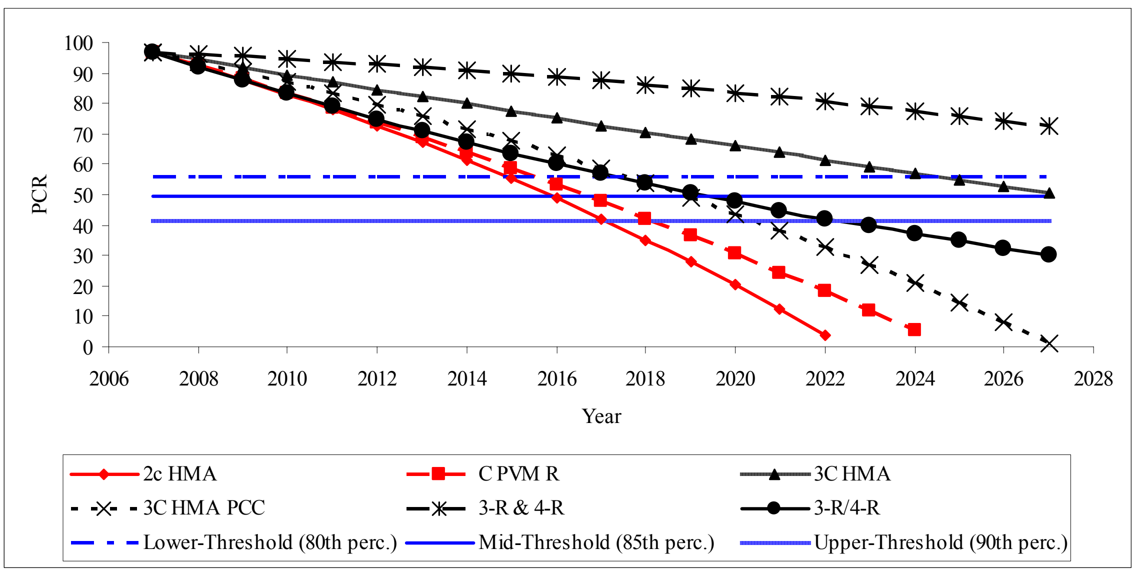

Figure 4.81 PCR forecasts and thresholds for urban non-interstates non-NHS

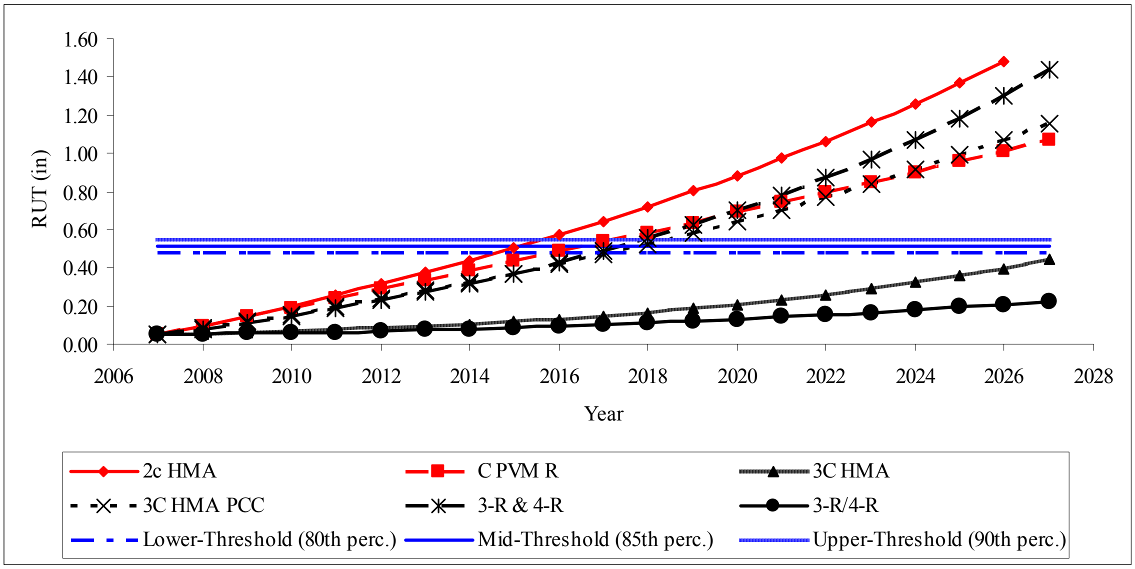

Figure 4.82 RUT forecasts and thresholds for urban non-interstates non-NHS

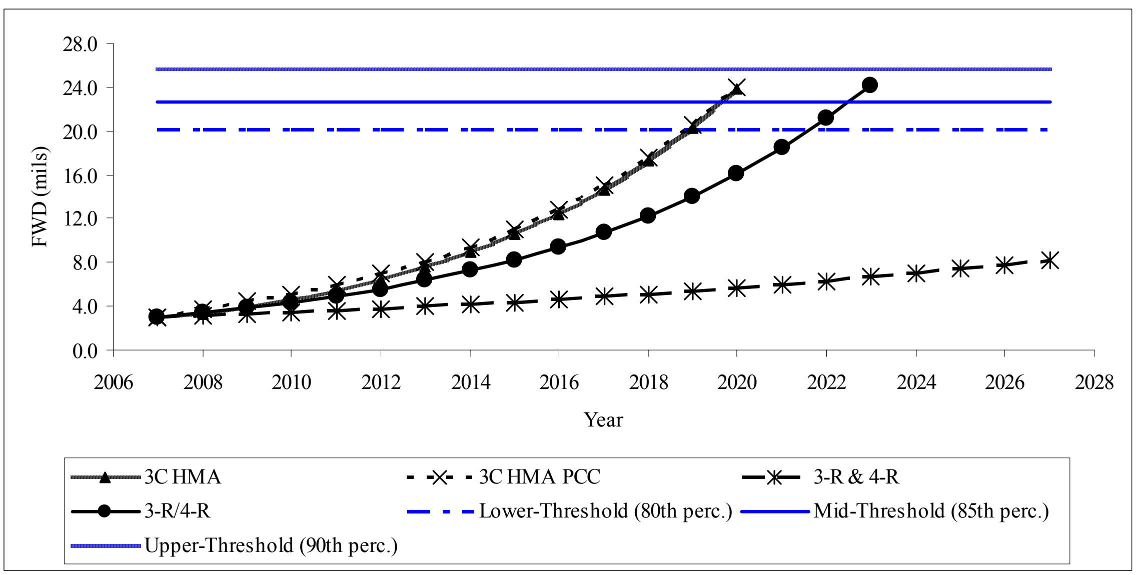

Figure 4.83 FWD forecasts and thresholds for urban non-interstates non-NHS

The resulting service lives of the treatments can be graphically approximated, and are presented in Table 4.48. Note that the service life is approximated satisfying the restriction $PI_n \leq PI_\kappa$, $PI_\kappa = \min\{PI_n\}$ of Equation (46). In words, the service life is defined as the time until any one of the pavement condition indicators surpasses its corresponding threshold. Given the assumptions discussed above, Table 4.48 shows that the average service life of 2C HMA is 10.2 years, of C PVM R 12 years, of 3C HMA 10.5 years, of 3C HMA PCC 11 years, of 3-R & 4-R 13.8 years, and of 3-R/4-R 14 years.

Table 4.48 Graphical approximation of the service life of the treatments

	Service Life (Lower-/Mid-/Upper- Year Estimates)					
	2C HMA	C PVM R	3C HMA	3C HMA PCC	3-R & 4-R	3-R/4-R
Rural Interstates	11/12/12	12/13/14	11/12/13	11/11/13	11/11/12	11/12/14
Rural Non-Interstates of the NHS	8/9/10	10/10/12	9/9/11	8/8/10	13/14/14	12/12/14
Rural Non-Interstates Non-NHS	11/11/12	10/12/14	10/11/14	10/12/15	19/20/21	11/13/14
Urban Interstates	10/11/12	11/13/14	9/10/12	12/13/14	11/12/12	12/15/15
Urban Non-Interstates of the NHS	8/9/10	13/14/15	8/10/12	9/11/13	9/12/13	10/19/20
Urban Non-Interstates Non-NHS	8/9/10	9/10/11	10/11/11	11/11/12	14/14/16	11/13/16
Treatment Overall Service Life Range	8-12	9-15	8-14	8-15	9-21	10-20

CHAPTER 5. CONCLUSIONS

5.1. Contribution of this Research

This study is of interest to individuals who are concerned about the estimation of the service life of commonly implemented pavement rehabilitation treatments. The intent of this research was to extend the traditional framework of pavement management, by formulating methodologies that enable transportation agencies to evaluate the effectiveness of their pavement treatments with respect to each treatment's service life. As such, the contributions of this study are the following:

- Past attempts to assess the service life of pavement treatments, being analytical in nature, have identified methods to individually model the pavement performance, or analyze their service lives. This research study provides a simple but comprehensive framework to estimate pavement service lives, by explicitly describing all intermediate steps of the process.

- With respect to pavement management, past research utilized single-equation methods to model the pavement performance, without accounting for potential simultaneous relationships among the performance indicators. This typically results in biased and inefficient estimators of the pavement performance, which in turn makes performance modeling and forecasting inaccurate and inconsistent. The proposed methodology provides a simple framework to account for these simultaneous relationships. The resulting pavement-performance models and equations are easy to implement and provide accurate forecasts, even though little information is needed (i.e., historical pavement condition data, traffic and truck loads, drainage condition, and rehabilitation cost).

- The segmentation of the pavement analysis accounts for 36 combinations of six pavement rehabilitation treatments and six road functional classes. This allows for a more accurate estimation of the performance and service life of the pavement, corresponding to each treatment and road functional class.

- The effect of surface deflection in pavement deterioration has not been extensively investigated in the literature. In the current study, surface deflection appears to play an important role in determining the pavement service life of structural pavement rehabilitation treatments.

The end product of this research is a quantitative tool that can be used at the project development phase to estimate the effects of different types of pavement rehabilitation treatments. A major contribution of this work is the demonstration of a general approach that can be applied for comprehensive analysis of the effects of pavement rehabilitation treatments, while taking into account specific characteristics of the pavement system. The results set forth herein provide a better understanding of the interrelationships among pavement rehabilitation treatments, pavement conditions, road functional classes, pavement service lives, traffic and truck loads, weather and soil conditions, and rehabilitation expenditures. The statistical techniques used result in consistent, efficient and lower-variance parameter estimates, relative to simple least squares methods. Given the complexity of the problem and the limitations of available data, this study should be viewed as an incremental step toward enabling transportation agencies to make better decisions regarding a number of pavement rehabilitation treatments, allowing the selection of treatment options that will last the longest within given budget limitations.

5.2. Discussion of Research Results and Lessons Learned

This research involved extensive data assembly and econometric model analysis. Econometric models were developed to assess and forecast the pavement performance and identify influential factors, and approximate the service life of the pavement treatments, all with a reference to the State of Indiana. The estimation and use of these models was the subject of considerable discussion in this study. The major research findings that can assist transportation agencies in making better decisions regarding standard rehabilitation treatment selection, in terms of their service lives and of identifying the most efficient allocation of resources, are summarized below.

- The performance and service lives of pavement rehabilitation treatments are not the same for all pavements. They depend on the treatment itself (i.e., two-course hot-mix asphalt (HMA) overlay with or without surface milling, concrete pavement restoration, three-course HMA overlay with or without surface milling; three-course HMA overlay with crack and seat of Portland cement concrete (PCC) pavement, 3-R (resurfacing, restoration and rehabilitation) and 4-R (resurfacing, restoration, rehabilitation and reconstruction) overlay treatments, and 3-R/4-R pavement replacement treatments), the road functional class where the road section (hence the pavement) is located (i.e., rural and urban interstates, non-interstates of the National Highway System (NHS), and non-interstates that do not belong to the NHS), the pavement condition (i.e., pavement roughness (IRI), pavement condition rating (PCR), rut depth, and for the structural treatments surface deflection), traffic and truck loads, drainage condition, weather (precipitation and temperature) and rehabilitation cost.

- Simultaneous relationships are found to exist among the pavement performance indicators (i.e., IRI, PCR, rut depth, and surface deflection). Therefore, the appropriate econometric technique to model the pavement performance is a seemingly unrelated regression equations approach, which accounts for these simultaneous relationships at an error cross-correlation level, but does not necessarily assumes that the indicators themselves are highly correlated and that each indicator depends on the others.

- Given some standard (estimated at sample mean/median) values, note that over a twelve-year period, two-course HMA overlay with or without surface milling treatments are found to have a forecasted average deterioration in IRI, PCR, and RUT of 72 in/mi, 46, and 0.48 inches, respectively. Concrete pavement restoration treatments, for the same twelve-year period, are found to have a forecasted average deterioration in IRI, PCR, and RUT of 83 in/mi, 41, and 0.49 inches, respectively. Three-course HMA overlay with or without surface milling treatments are found to have a forecasted average deterioration in IRI, PCR, RUT, and FWD of 62 in/mi, 33, 0.33 inches, and 10.5 mils, respectively. Three-course HMA overlay with crack and seat of PCC pavement treatments are found to have a forecasted average deterioration in IRI, PCR, RUT, and FWD of 47 in/mi, 43, 0.43 inches, and 7.2 mils, respectively. 3-R and 4-R overlay treatments are found to have a forecasted average deterioration in IRI, PCR, RUT, and FWD of 46 in/mi, 31, 0.36 inches, and 5.5 mils, respectively. And 3-R/4-R pavement replacement treatments are found to have a forecasted average deterioration in IRI, PCR, RUT, and FWD of 60 in/mi, 37, 0.31 inches, and 6 mils, respectively. Given some standard (estimated at sample mean/median) values, the service life of two-course HMA overlay with or without surface milling ranges from 8 to 12 years; of concrete pavement restoration from 9 to 15 years; of three-course HMA overlay with or without surface milling from 8 to 14 years; of three-course HMA overlay with crack and seat of PCC pavement from 8 to 15 years, of 3-R and 4-R overlay treatments from 9 to 21 years; and of 3-R/4-R pavement replacement treatments from 10 to 20 years.

- Surface milling does not seem to play an important role in determining pavement condition of the two-course and three-course HMA overlay pavement rehabilitation treatments.

5.3. Directions for Future Research

The data collected and generated for the purpose of this study reported herein, have produced a better understanding of the estimation mechanisms of the pavement performance and service lives. The estimation results for various pavement rehabilitation treatments can enhance decision-makers' understanding of how pavement deteriorates, and how and when pavement rehabilitation should be initiated. However, these results are subject to some limitations inherent in the models and methods used, available data sources, and research scope. These limitations underscore the need for careful research and additional data collection and analysis. This is essential to make certain that the selection of the appropriate pavement rehabilitation treatment ensures the most efficient allocation of resources. The findings and lessons learned from this study coupled with these considerations indicate the following key directions for future research.

- Model estimation and verification for pavements that their completed life-cycle has been documented. This study involved substantial effort to accurately and credibly forecast pavement performance, using historical data and projecting the pavement performance in time. The econometric models presented in this study could have benefited considerably by having information on the actual condition of pavements whose condition has failed or completed a full life-cycle. This would reduce forecasting errors since actual data (and not forecasts) would be used, and would be ideal to conduct an *ex post facto* pavement performance modeling to validate the forecasted results.

- Consideration of additional pavement condition indicators and characteristics in the pavement performance modeling framework. Although the four pavement condition indicators (i.e., IRI, PCR, rut depth, and surface deflection for structural treatments) appear to provide a good representation of the pavement performance, there are a number of condition indicators and characteristics that would supplement the results and potentially provide some new findings. For example, skid resistance (pavement friction), alligator cracking index, pavement distress index, pavement serviceability rating, thickness of surface course, thickness of base course, rubber solid content, asphalt viscosity, asphalt content, and so on.

- Incorporation of space in the methodological framework. This study assumes that pavement performance and service lives are independent of space (i.e., the specific location of the pavement or of the road section). However, spatial relationships may exist among neighboring road sections that affect the pavement performance or service life. For example, the pavement performance of a road section may be influenced by the performance of the neighboring road sections, or from the characteristics of the neighboring road sections. These spatial effects include spatial dependence and spatial heterogeneity. Spatial dependence (also known as spatial autocorrelation) is the co-variation of properties within a spatial system resulting in systematic spatial patterns or observable clusters. From an econometric viewpoint, spatial dependence violates the standard statistical assumption of independence of the errors or exogeneity of the regressors, which may lead to biased parameter estimates and yield unreliable significance tests. Spatial heterogeneity refers to discrete or continuous space-varying structural relationships describing space-related factors that systematically vary across the population. Therefore, investigation of these underlying spatial dynamics would explore an additional dimension to pavement rehabilitation treatment practices.

LIST OF ABBREVIATIONS

2C HMA	Two-Course HMA Overlay With or Without Surface Milling
2SLS	Two-Stage Least Squares
3C HMA	Three-Course HMA Overlay With or Without Surface Milling
3C HMA PCC	Three-Course HMA Overlay with Crack and Seat of PCC Pavement
3-R	Resurfacing, Restoration and Rehabilitation
3-R & 4-R	3-R and 4-R Overlay Treatments
3-R/4-R	3-R/4-R Pavement Replacement Treatments
3SLS	Three-Stage Least Squares
4-R	Resurfacing, Restoration, Rehabilitation and Reconstruction
AADT	Annual Average Daily Traffic
AASHO	American Association of State Highway Officials
AC	Asphalt Concrete
ACI	Alligator Cracking Index
ADOT	Arizona Department of Transportation
ANN	Artificial Neural Network
AZ	Arizona
C PVM R	Concrete Pavement Restoration
CEE	Cost Effectiveness Evaluation
COST	Treatment Contract Final Cost per Mile (USD)
COST 50K	Treatment Contract Final Cost per Mile (less than 50,000USD)
CRCP	Continuously Reinforced Concrete Pavements
d.o.f.	Degrees of Freedom
DOT	Department of Transportation

DR 1	Drainage Class: Excessively or Somewhat Excessively Drained
DR 2	Drainage Class: Excessively, Somewhat Excessively or Well Drained
DR 3	Drainage Class: Excessively, Somewhat Excessively, Well, or Moderately Well Drained
DR 4	Drainage Class: Somewhat Poorly, Poorly, or Very Poorly Drained
DR 5	Drainage Class: Poorly or Very Poorly Drained
DRL	Deterioration Reduction Level
DRR	Deterioration Reduction Rate
FHWA	Federal Highway Administration
FN	Friction Number
FWD	Falling Weight Deflection (or Deflectometer)
FWD base	Base (Right After Treatment) Surface Deflection (mils)
FWD base+1	FWD Measured One Year After the Base Year (mils)
FWD base+2	FWD Measured Two Years After the Base Year (mils)
FWD base+3	FWD Measured Three Years After the Base Year (mils)
FWD t	Surface Deflection in Analysis Year t (mils)
GASB	Governmental Accounting Standards Board Statement
GLS	Generalized Least Squares
HDM	Highway Design and Maintenance
HMA	Hot-Mix Asphalt
ID	Idaho
IN	Indiana
INDOT	Indiana Department of Transportation
IRI	International Roughness Index
IRI base	Base (Right After Treatment) IRI (in/mi)
IRI base+1	IRI Measured One Year After the Base Year (in/mi)
IRI base+2	IRI Measured Two Years After the Base Year (in/mi)
IRI base+3	IRI Measured Three Years After the Base Year (in/mi)

IRI t	IRI in Analysis Year t (in/mi)
JGLS	Joint Generalized Least Squares Estimation
JRCP	Jointed Reinforced Concrete Pavement
KBES	Knowledge-Based Expert Systems
LL	Log-Likelihood
LRT	Likelihood Ratio Test
LTPP	Long Term Pavement Performance
M,R&R	Maintenance, Rehabilitation and Reconstruction
MAPE	Mean Absolute Percent Error
MBC	Maintenance-by-Contract
MCI	Miscellaneous Cracking Index
MD	Maryland
MIH	Maintenance-in-House
MS	Mississippi
NC	North Carolina
NCHRP	National Cooperative Highway Research Program
NE	Nebraska
NHS	National Highway System
NHTSA	National Highway Traffic Safety Administration
NRC	National Research Council
NV	Nevada
OH	Ohio
OLS	Ordinary Least Squares
OR	Oregon
PCC	Portland Cement Concrete
PCI	Pavement Condition Index
PCR	Pavement Condition Rating
PCR base	Base (Right After Treatment) PCR
PCR base+1	PCR Measured One Year After the Base Year
PCR base+2	PCR Measured Two Years After the Base Year

PCR base+3	PCR Measured Three Years After the Base Year
PCR t	PCR in Analysis Year t
PDI	Pavement Distress Index
PE	Percentage Error
PI	Performance Indicator
PJ	Performance Jump
PMS	Pavement Management System
PRC	Pavement Rehabilitation Case
PPS	Pavement Preservation Strategy
PQI	Pavement Quality Index
PSI	Present Serviceability Index
PSR	Pavement Serviceability Rating
Ride	Ride Quality
RN	Roughness Number
RUT	Rut Depth
RUT base	Base (Right After Treatment) Rut Depth (inches)
RUT base+1	Rut Depth Measured One Year After the Base Year (inches)
RUT base+2	RUT Measured Two Years After the Base Year (inches)
RUT base+3	RUT Measured Three Years After the Base Year (inches)
RUT t	Rut Depth in Analysis Year t (inches)
SCI	Surface Condition Index
SHRP	Strategic Highway Research Program
SN	Skid Number
SURE	Seemingly Unrelated Regression Equations
Trucks	Cumulative (Over Treatment Contract Period) Daily No. of Trucks (in 1000s)
USD	U.S. Dollars
UT	Utah
WA	Washington
WY	Wyoming

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